

Designing with Thin Gauge

Presented by

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- Demand for electrical device efficiency gains which started decades ago due to economic factors have accelerated, propelled by the unprecedented rise in energy costs and the alleged impact of energy consumption on global weather instability.

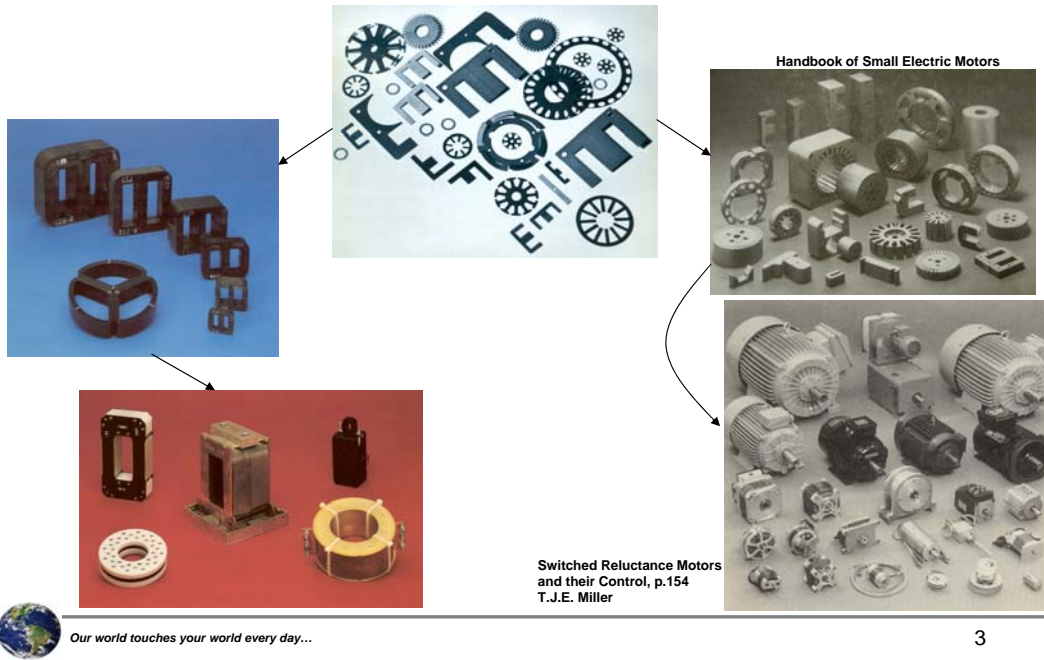
Agenda

- Introduction
- Manufacturing Process
- GOES versus NGOES
- Motor Efficiency
- Loss Factors
- NGO Thin Gauge (Arnon)



- Over the last several years I've spoken about permanent magnets. However, the magnetic material that is utilized in far greater tonnage than magnets is the family of soft magnetic materials, especially Iron-Silicon whose usage spans both motor/generator and transformer/inductor applications.
- Often referred to as Electrical Steel, Iron Silicon is available in both Grain Oriented (GOES) and Non-Oriented (NGOES) forms.

Two Main Applications for Electrical Steel



- There are two main uses for Electrical Steel: Transformers/Inductors and Motors/Generators.
- Transformers are used not only for Electrical Power Distribution, but in virtually every power supply in every electrically powered electronic device in offices and homes.
- Motors have moved from industrial uses in the 1800 and early 1900's to home and automotive uses. In homes for example, we use motors in garage door openers, washing machines and dryers, furnaces for home heating, refrigerator compressor pumps, bathroom exhaust fans, garbage disposals, and electric powered hand tools.
- Motor usage in automobiles has expanded to include windshield wiper motors, seat adjusting motors, starters, cooling fans, passenger compartment fans, alternators, etc. Note however, many of these use low carbon steel cans for low cost with laminations reserved for higher output motors/generators.
- The newest example of lamination steel use in cars is the electric drive motor of hybrids or full electric vehicles.

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- Higher frequency operation is possible because of reduced eddy current related loss in select lamination materials.
- Iron-Silicon laminations are more expensive than low carbon steel and their use has been reserved for high energy density, high rpm motors and generators.
- In defense of the manufacturers, the process for making lamination-ready Fe-Si strip involves many processing steps and utilizes expensive manufacturing equipment.

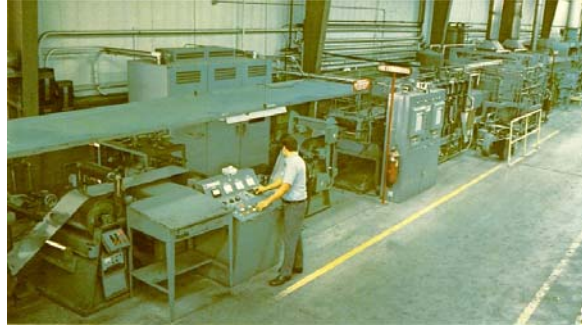
Manufacturing Steps, NGOES

- Melting and continuous casting of slabs
- Hot Rolling to thickness of ~2 mm
- Pickling and cold rolling to intermediate gauge
- Annealing (750 to 900 °C)
- Cold rolling to final gauge (0.13 – 0.35 mm)
- Decarburization and re-crystallization anneal (830 – 900 °C)
- Final anneal (850 – 1100 °C)
- Coating (washing, coating, drying)
- Slitting
- Punching to shape



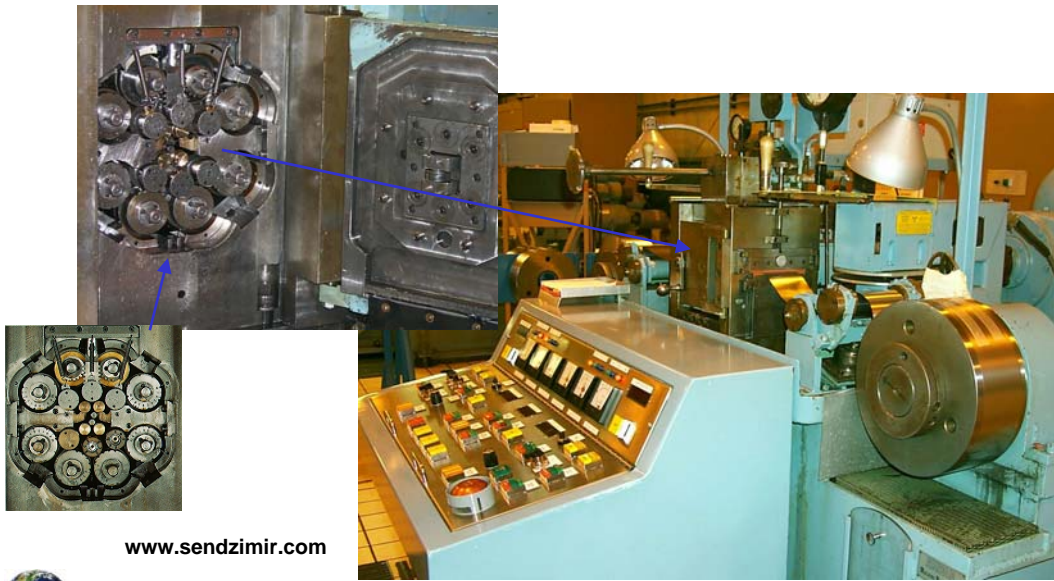
- There are at minimum 10 manufacturing steps utilizing equipment such as melting furnaces, hot and cold rolling mills, atmosphere treatment furnaces, acids and inorganic coating materials, tool steel precision slitters, etc.
- Looking at the items above shown in blue.

Decarburization, Re-crystallization and final Anneal



- Re-crystallization and annealing is performed in continuous atmosphere furnaces.
- The strip can be seen exiting the furnace at the left of this photo...

Sendzimir Mill Rolling to Final Gauge

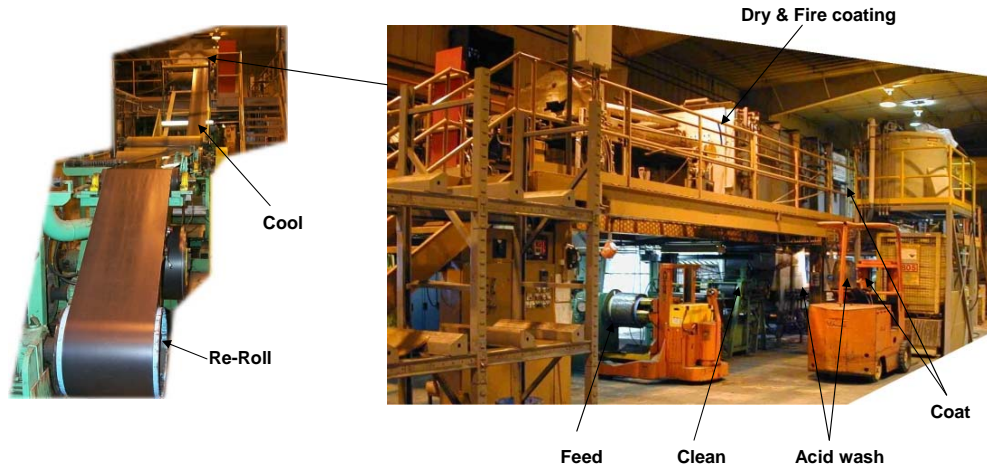


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- For thin gauge, specialized rolling mills are used to achieve uniform cross-strip thickness and flawless surfaces on material down to 0.001" (0.025 mm).
- Arnold does, incidentally, roll other alloys to as little as 85 millionths of an inch (0.000085") on Sendzimir mills.
- The Sendzimir mill uses small diameter rolls to reduce the strip thickness. The small rolls are backed-up by larger rolls to eliminate bending of the small rolls under intense compressive stress.

Surface Treatment and Coating



- Surface coating includes steps of acid wash, coating and firing the coating onto the strip.

Slitting



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- While it may be more efficient to process wide strip, the specific application often requires a narrow section either to match the device size or to maximize utilization.
- Significant material loss occurs when the center of a round lamination is punched-out.
- Many larger devices benefit from segmenting the laminations and using an alternated stacking arrangement to: 1) maximize material usage and minimize reluctance losses due to gaps in the lamination stack.

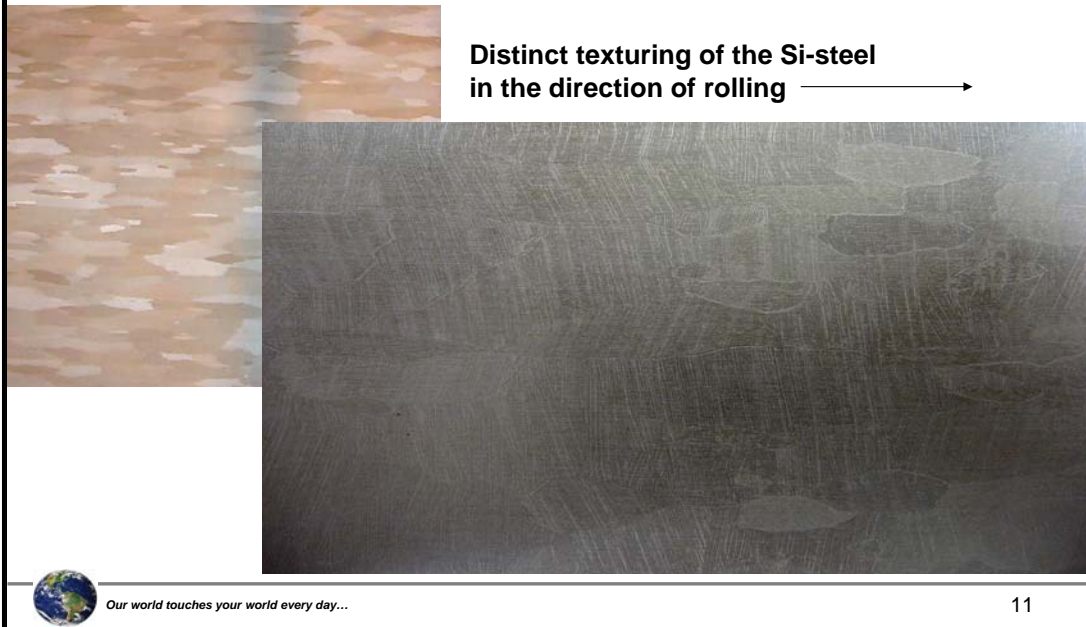
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- Grain Oriented and Non-Grain Oriented Electrical Steel.

GOES Texturing



- Iron-silicon consists of BCC (body-centered cubic) crystals which, during rolling, are stretched and flattened. If they are left in that state, the magnetic properties are maximized in the rolling direction, that is along the length of the strip.
- In these two photos we can see the elongated and flattened structure.

GOES versus NGOES



- However, when a final annealing heat treat is performed, we can achieve close to isotropic properties within the plane of the strip.
- This is exemplified by the almost total elimination of the grain structure as seen in the photo to the right.

Directional Properties of Si-Steel (GOES)

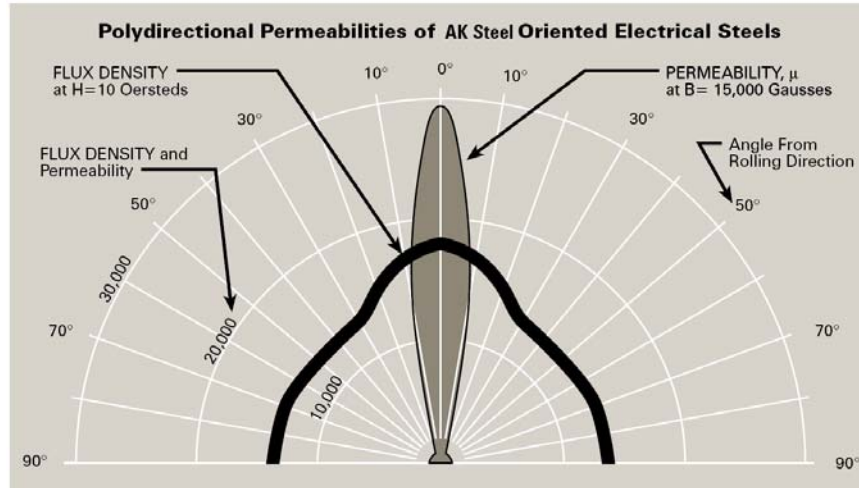


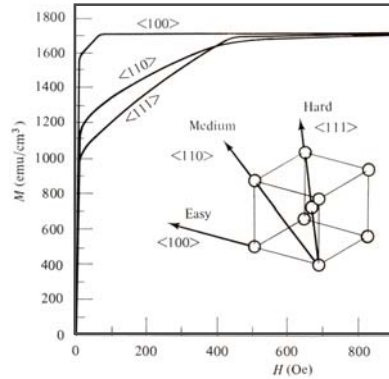
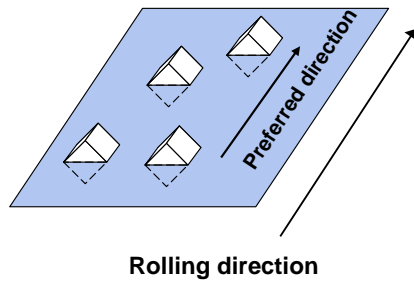
Figure 3. Tests made on Epstein samples cut at various angles to rolling direction, stress annealed after shearing. Negligible joint effects. Assumed density 7.65 grams per cubic centimeters.



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- This chart from AK steel for grain oriented silicon iron illustrates the difference in magnetic properties in the rolling direction (straight up and down) and at angles at up to 90° from the rolling direction (left to right).
- Maximum performance is achieved by application of the material with the strip in the same direction that flux is expected.
- In contrast, NGOES shows only a 10-20% variation in properties within the plane of the strip and can be used in any orientation.

Understanding the Structure



- Iron crystals in Fe-Si are BCC (Body Centered Cubic). As shown in the illustration at the right, the easy axis (of magnetization) is along the $\langle 100 \rangle$ crystal axis.
- The “hard” axis is from one corner to the diagonally opposite corner: the $\langle 111 \rangle$ crystal axis.
- To reiterate, effective application of the material requires using the strip in the same direction that flux is expected.

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Discussion regarding the use of Fe-Si needs to include consideration of motor efficiency to justify the more expensive material (i.e., more expensive than low carbon steel).

Motor Efficiency

“...~57% of the generated electric energy in the United States is utilized [consumed] by electric motors powering industrial equipment. In addition, more than 95% of an electric motor’s life-cycle cost is the energy cost.”

The Next Generation Motor, IEEE Industry Applications, January / February 2008, p.37



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Electric Operating Cost


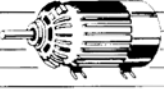
		
	Automobile	60 HP* Motor
Purchase Price	\$16,000	\$4,000
Annual Use	12,000 miles/yr.	4,000 hrs.**
Efficiency	30 miles/gallon	89.2%
Fuel/Energy Cost	\$3.50 /gallon	5.6c kwh
Annual Operating Cost	\$1400/yr.	\$10,036/yr
Operating cost as % of Purchase Price	9%	250%

Figure 1. First Cost is not the Last Cost

*60 HP; equivalent to 50.18 kw capacity

**Based on 2-shift operation

Art courtesy of Ontario Hydro

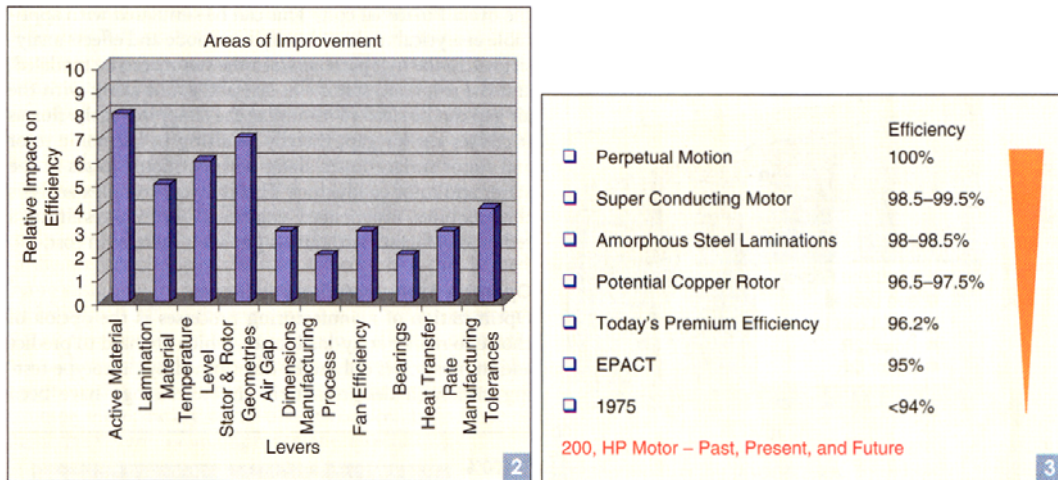
From AEC (North Carolina Alternative Energy Corporation), updated with current gas prices, www.p2pays.org/ref/17/16897.pdf



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- This chart has been updated with current gasoline pricing. Electric costs are likely to rise commensurate with gas but are not changed here.
- It is obvious that more attention must be paid to total operating costs, not just initial purchase price. Our industry needs to help educate the customer to “get beyond the price tag.”.

Motor Efficiency



Impact of the possible areas of improvement for the performance of induction motors.

Typical efficiency levels over time.

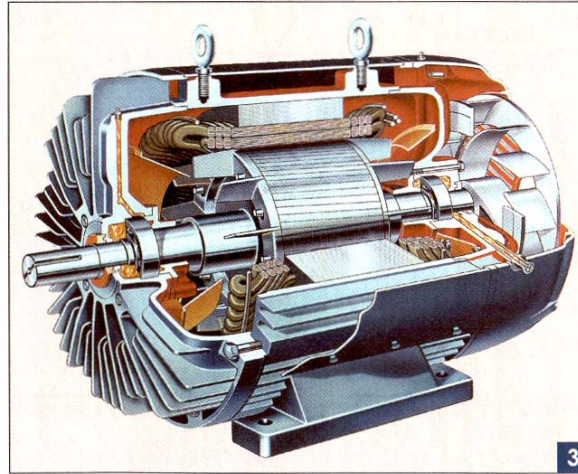
Increased Efficiency versus Increased Reliability, IEEE Industry Applications, January / February 2008, p.29



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- Efficiency increase is affected by many facets of the motor. This estimates that close to 5% of total energy loss is due to current lamination materials and designs.
- With targets of 96% plus efficiency, it is imperative to optimize lamination material.

Motor Failures and Temperature



Typical TEFC motor.

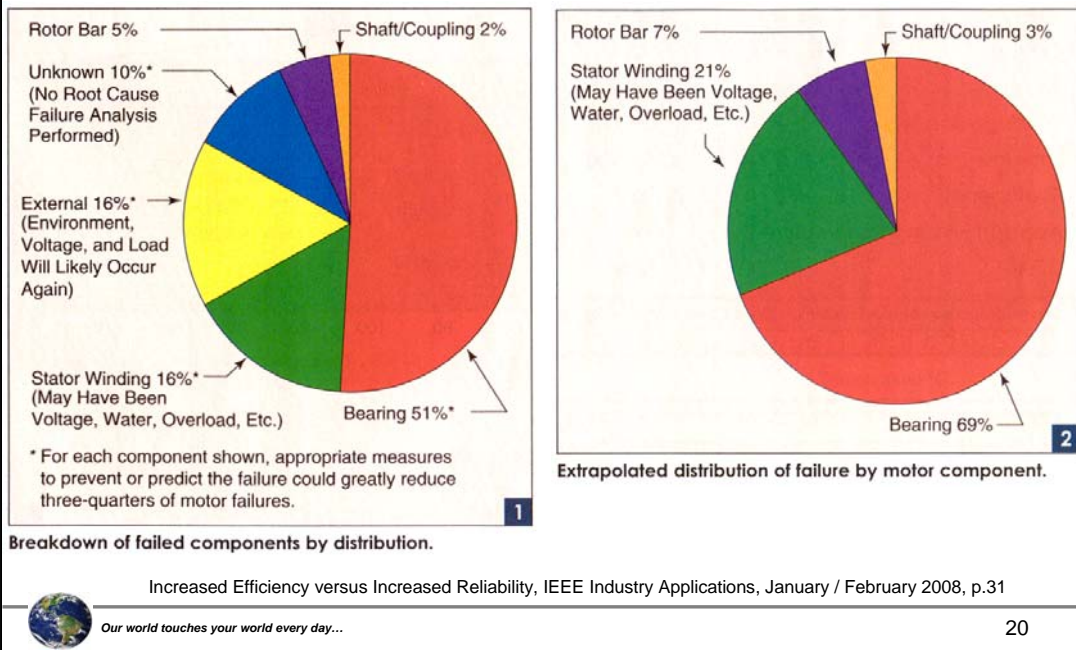
Increased Efficiency versus Increased Reliability, IEEE Industry Applications, January / February 2008, p.31



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- Example of TEFC motor used in the following referenced study.

Motor Failures and Temperature



- Bearings and stator windings are the two most common causes of failure in a typical TEFC motor.
- One of the most severe detractors to long life is **heat** most of which originates in motor inefficiency.
- Per the article: "...every 10 °C reduction in [wire] insulation temperature doubles the insulation life."

Loss Distribution

COMPARISON OF LOSS DISTRIBUTION BY PERCENT FOR MOTORS TESTED
 IN THE EASA/AEMT STUDY [12].

Losses	Two-Pole Average	Four-Pole Average	Design Factors Affecting Losses
Core losses (W_c)	19%	21%	Electrical steel, air gap, saturation, supply frequency, condition of interlaminar insulation
Friction and windage losses (W_{fw})	25%	10%	Fan efficiency, lubrication, bearings, seals
Stator I ² R losses (W_s)	26%	34%	Conductor area, mean length of turn, heat dissipation
Rotor I ² R losses (W_r)	19%	21%	Bar and end ring area and material
Stray load losses (W_l)	11%	14%	Manufacturing processes, slot design, air gap, condition of air gap surfaces and end laminations

Increased Efficiency versus Increased Reliability, IEEE Industry Applications, January / February 2008, p.33

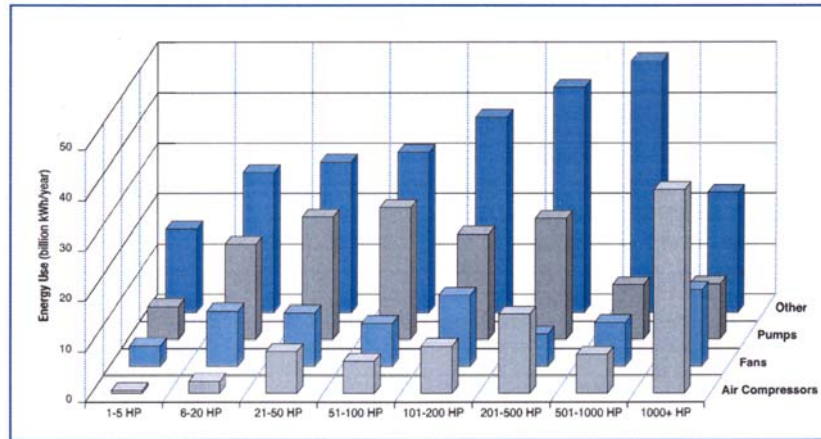


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- 20% of energy loss in the motors under study is Core Loss, most of which is attributed to the lamination material either directly or indirectly.

Energy Consumption by Motor Size



Motor system energy consumption (Adapted from information in the *United States Industrial Electric Motor Systems Market Opportunities Assessment*, available online at www.eere.energy.gov/industry/bestpractices/.)



- Large industrial motors consume greater amounts of electric power than smaller motors.

Energy Policy Act Efficiency Targets

Number of Poles Motor Horsepower	Nominal Full-Load Efficiency					
	OPEN MOTORS			CLOSED MOTORS		
	6	4	2	6	4	2
1	80.0	82.5	-	80.0	82.5	75.5
1.5	84.0	84.0	82.5	85.5	84.0	82.5
2	85.5	84.0	84.0	86.5	84.0	84.0
3	86.5	86.5	84.0	87.5	87.5	85.5
5	87.5	87.5	85.5	87.5	87.5	87.5
7.5	88.5	88.5	87.5	89.5	89.5	88.5
10	90.2	89.5	88.5	89.5	89.5	89.5
15	90.2	91.0	89.5	90.2	91.0	90.2
20	91.0	91.0	90.2	90.2	91.0	90.2
25	91.7	91.7	91.0	91.7	92.4	91.0
30	92.4	92A	91.0	91.7	92.4	91.0
40	93.0	93.0	91.7	93.0	93.0	91.7
50	93.0	93.0	92A	93.0	93.0	92.4
50	93.6	93.6	93.0	93.8	93.6	93.0
75	93.6	94.1	93.0	93.6	94.1	93.0
100	94.1	94.1	93.0	94.1	94.5	93.6
125	94.1	94.5	93.6	94.1	94.5	94.5
150	94.5	95.0	93.6	95.0	95.0	94.5
200	94.5	95.0	94.5	95.0	95.0	95.0

Increasing Efficiency Targets

75.5%

95.0%



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- This chart emphasizes the energy efficiency requirements of higher HP motors since that is where the greatest energy savings will accrue.

Additional Motor Efficiency Information

- Energy Efficient Electric Motor Selection Handbook
 - www.wbdg.org/ccb/DOE/TECH/ce0384.pdf
- Buying an Energy Efficient Electric Motor
 - www1.eere.energy.gov/industry/bestpractices/pdfs/mc-0382.pdf
- Consortium for Energy Efficiency
 - www.cee1.org/ind/mot-sys/mtr-ms-main.php3
- Efficient Electric Motor Systems for Industry
 - www.osti.gov/bridge/servlets/purl/10112522-FoENQM/webviewable/10112522.PDF
- Efficient Electric Motor Systems: SEEEM
 - www.asiapacificpartnership.org/BATF/BATF%20Projects%20Workshops/Motors%20WS-SEEEM-brunner.pdf
- Development of Ultra-Efficient Electric Motors
 - www.osti.gov/bridge/servlets/purl/928973-hsePV1/928973.PDF
- Electric Motor Systems in Developing Countries: Opportunities for Efficiency Improvement
 - www.osti.gov/bridge/servlets/purl/10187187-n23Ohm/native/10187187.PDF



- There is a wealth of information on the internet. Here are just a few additional useful links.

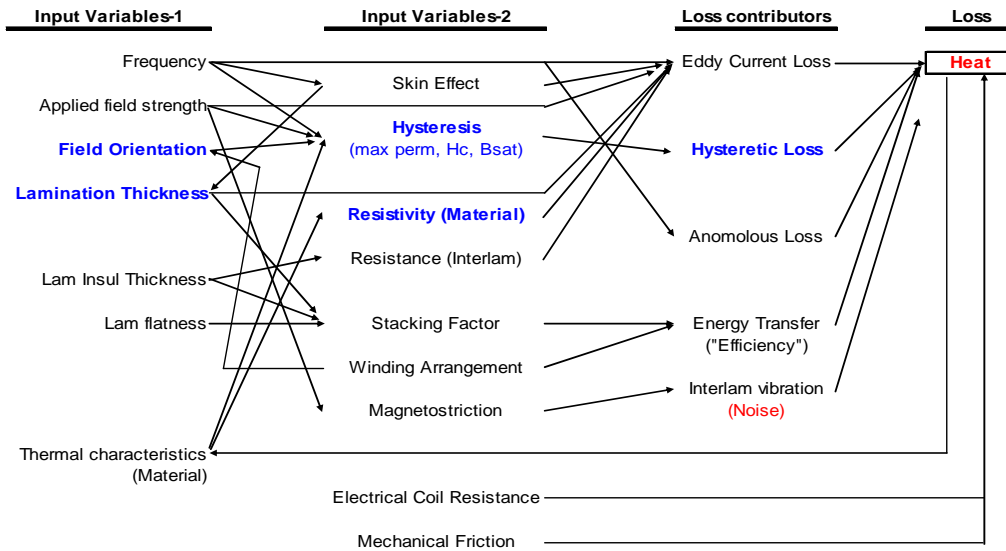
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- Fe-Si is more expensive than low carbon steel and thin gauge Fe-Si is more expensive than thick gauge.
- Therefore, to justify the usage of thin gauge Fe-Si, there must be an advantage to counterbalance the higher cost.

Loss Variables



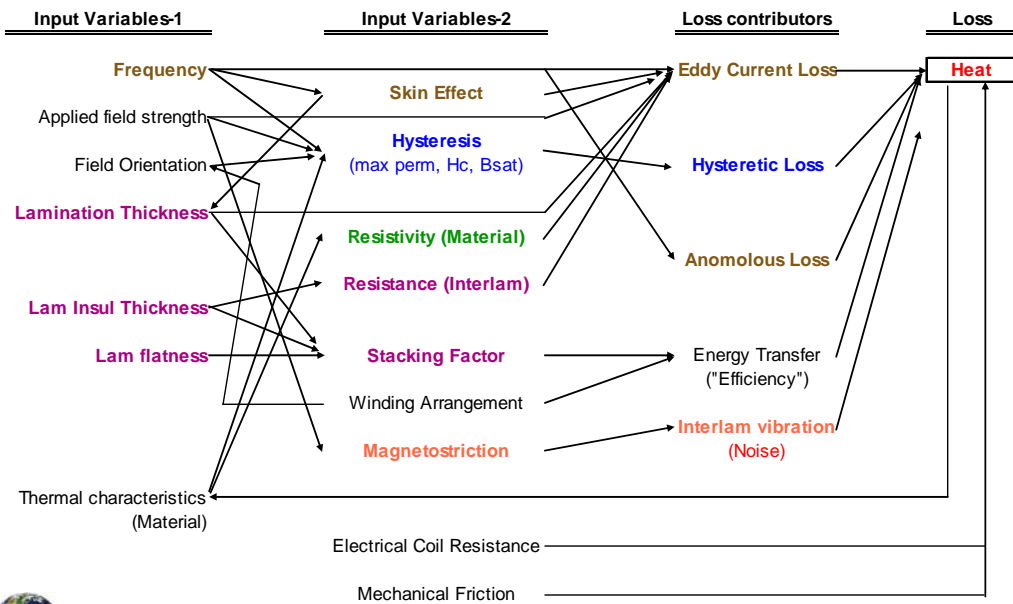
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- This busy slide is meant to show the complex set of variables involved with selecting the proper material grade and thickness.
- Lower efficiency is the result of energy being converted to heat.
- Note that many of the variables are interactive. One variable can affect another variable. For example, switching frequency affects how deep the field will penetrate a lamination which affects required lamination thickness which affects stacking factor, etc.
- The five items highlighted in blue are directly associated with thin gauge Fe-Si. That is, the use of thin gauge Fe-Si can minimize the losses associated with these five items over the use of thicker gauge or low carbon steels.

- 1: Hysteresis
- 2: Eddy Current
- 3: Laminations
- 4: Magnetostriction
- 5: Material Resistivity

Loss Variable Categories









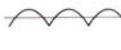

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- These variables can be grouped into similar categories for discussion.
- 5 groups have been created here.

Waveforms

Note: In these formulas N is the number of turns in the winding across which the voltage is developed. A is the cross-sectional area of the core around which the winding is placed. If the area is expressed in square centimeters, the flux density will be in gauss. If the area is expressed in square inches, the flux density will be in maxwells per square inch. Time t is in seconds. Frequency f is in hertz. Voltage E in in volts. Current I is in amperes. Inductance L is in henries.

Table 1.1 Maximum Flux Density Formulas for Commonly Occurring Functions

Function	Waveform	Formula
1. Sine wave voltage (steady-state)		$B_{max} = \frac{E_{rms} \times 10^8}{4.44NAf}$
2. Symmetrical square wave voltage		$B_{max} = \frac{E_{pk} \times 10^8}{4NAf}$
3. Interrupted symmetrical square wave voltage		$B_{max} = \frac{E_{pk} \times t \times 10^8}{2NA}$
4. Half sine wave voltage pulse		$B_{max} = \frac{E_{pk} \times 2 \times t \times 10^8}{\pi NA}$
5. Unidirectional rectangular voltage pulse		$B_{max} = \frac{E_{pk} \times t \times 10^8}{NA}$
6. Full-wave-rectified single-phase sine wave voltage (ac component only)		$B_{max} = \frac{E_{dc} \times 10^8}{19.0NAf}$
7. Half-wave-rectified three-phase sine wave voltage (ac component only)		$B_{max} = \frac{E_{dc} \times 10^8}{75.9NAf}$
8. Full-wave-rectified three-phase sine wave voltage (ac component only)		$B_{max} = \frac{E_{dc} \times 10^8}{664NAf}$
9. Current	Any	$B_{max} = \frac{LI_{max} \times 10^8}{NA}$

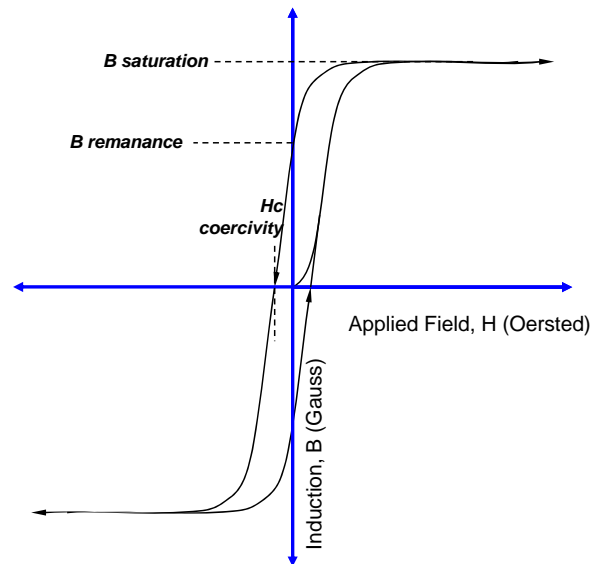
Handbook of Transformer Design & Application, p. 1.6



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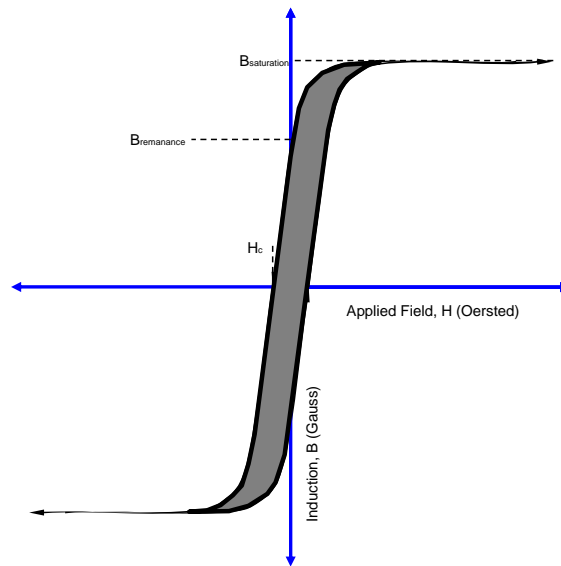
- Before we begin examining magnetic and electrical properties of the material, it is necessary to understand that the affects upon the material are due to the rate and magnitude of applied field change.
- While we consider a sinusoidal wave form to be most common, developments in electronic controls over the past two decades have allowed application of complex waveforms for both control and efficiency.
- Some of these waveforms produce more rapid field changes than suggested by the over riding frequency. One example of this is a pulse field waveform.
- By the way, transformers and chokes are also exposed to these waveforms and affects upon their performance.

1: Hysteresis Curve



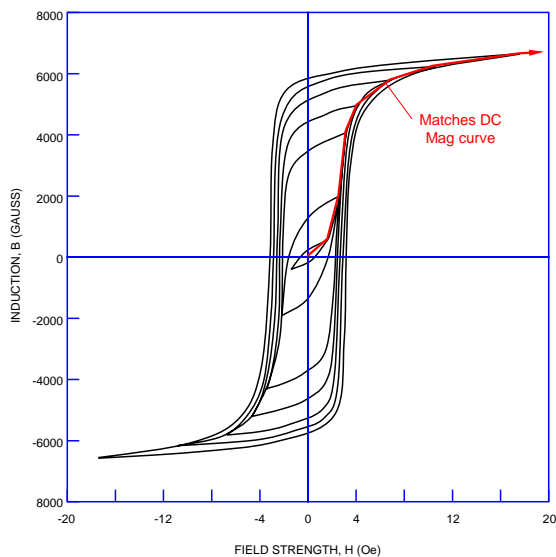
- A sinusoidal magnetic field applied to a ferromagnetic material will drive induction back and forth along the horizontal axis as shown in this hysteresis curve. As the applied field increases, the induction increases, etc.
- As it proceeds in the first quadrant, the material can become fully saturated.
- However, as the H field decreases toward the negative region (2nd quadrant), the induction does not follow the exact same path. Instead, there is a lag--or hysteresis in the induction.
- Even when the field reaches zero ($H=0$), there is still some induction remaining in the material. This is called the remanant flux density, or B_r .
- To bring the induction in the material down to zero, the H field must be driven past zero into a negative value called H_c or H_cB -- this is the “coercivity” of the material.
- As the sinusoidal field continues to go through its cycles, this behavior is repeated in both directions (polarities).

1: Hysteresis Loss



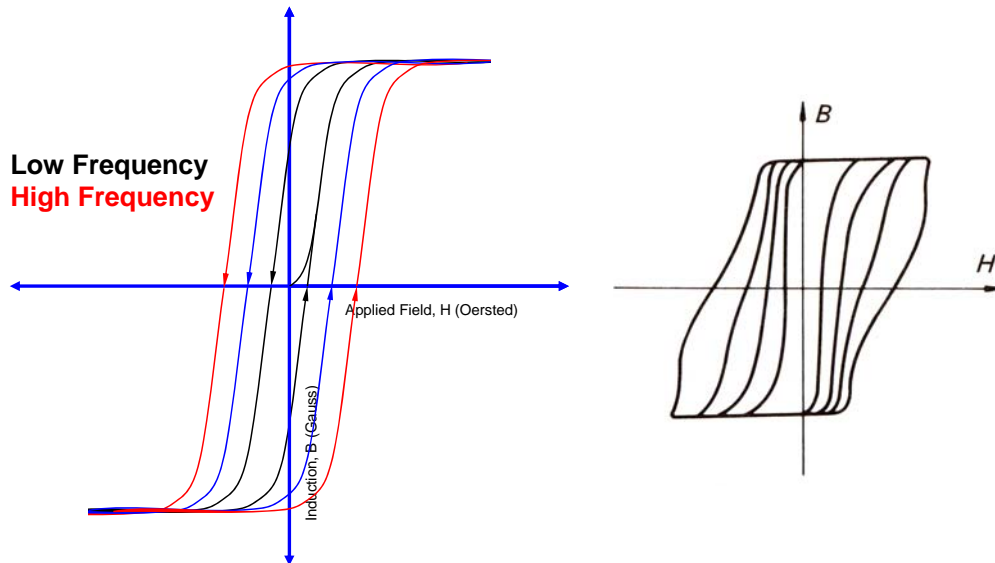
- One implied property from these hysteresis curves is that there is significant energy absorption, represented by the area inside the hysteresis curve.
- In soft magnetic applications, this energy absorption manifests itself as “hysteresis loss” (alternatively, “hysteretic loss”).
- The hysteresis loss is the energy absorbed by the material as it being magnetized in one direction then re-magnetized in the reverse direction.

1: Hysteresis Curve - Minor Loops



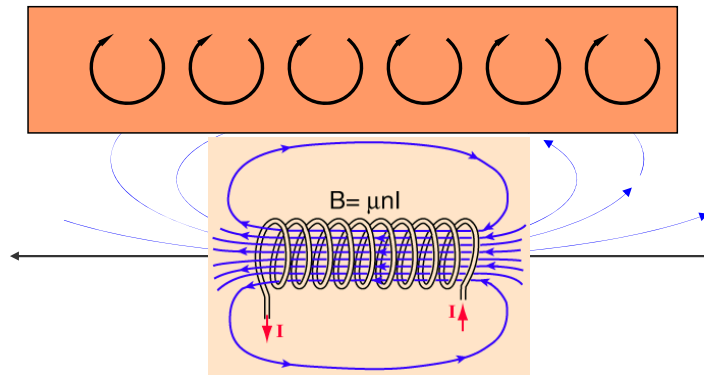
- In a PM motor, the material is unlikely to be driven to saturation. As a result, the material will be using “minor” loop properties.
- This is a series of super-imposed minor hysteresis curves. It can be clearly seen that the induction response differs greatly depending upon the level of applied field.
- The energy loss will be equal to the area within the specific minor loop experienced by the lamination material.
- Since not all the material will see the same externally applied field, there will be unequal energy loss from spot to spot within the lamination structure.
- The more square loop the material, the greater the sensitivity to small changes in applied field.

1: Hysteresis Loss - Frequency Effects



- Additionally, when the frequency of the applied field is increased, it has been found that hysteresis loss also increases.
- This is manifested as an increase in the area within the hysteresis curve(s).
- As the frequency continues to increase, however, another aspect of core loss begins to appear, causing not only an enlargement of the area inside the curve, but also distortion.
- This distortion is due in large part to eddy currents.

2: Eddy Current Loss



<http://hyperphysics.phy-astr.gsu.edu/hphys.html>

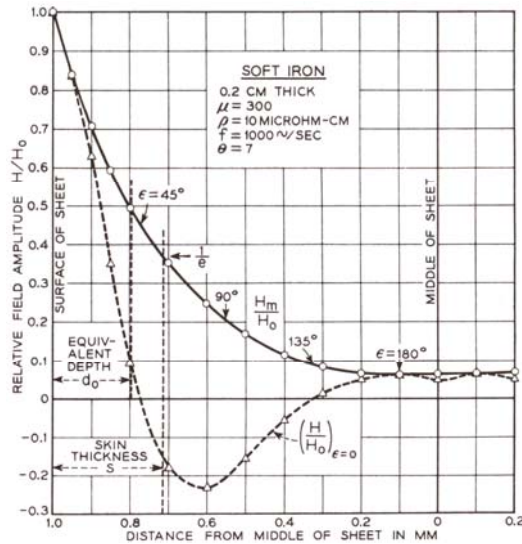


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- As the magnetic field alternates through a conductor, eddy currents are created in the material. These are localized currents, flowing in a closed path within the lamination. In accordance with Lenz's law, these currents oppose change in the field that is inducing the eddy currents.
- The creation of these currents requires energy, and therefore is a source of energy loss.
- Eddy current loss is in addition to hysteresis loss.
- It should be noted that eddy currents can occur in any conductive material including non-magnetic copper and aluminum. In fact, it can be shown that eddy currents in a non-magnetic conductor can exert significant braking effect relative to a moving magnet (hysteresis brakes).
- The key point here is that eddy currents are caused either by a permanent magnet moving in relation to the conductive material or by a changing electromagnetic field generated by current flow in a conductor.

2: Eddy Current Skin Depth



$$s = \frac{5030}{\sqrt{\mu f / (\rho \times 10^{-9})}}$$

By definition then, when $s = 1/e$, $H \sim 36.8\%$ of the surface field, H_0

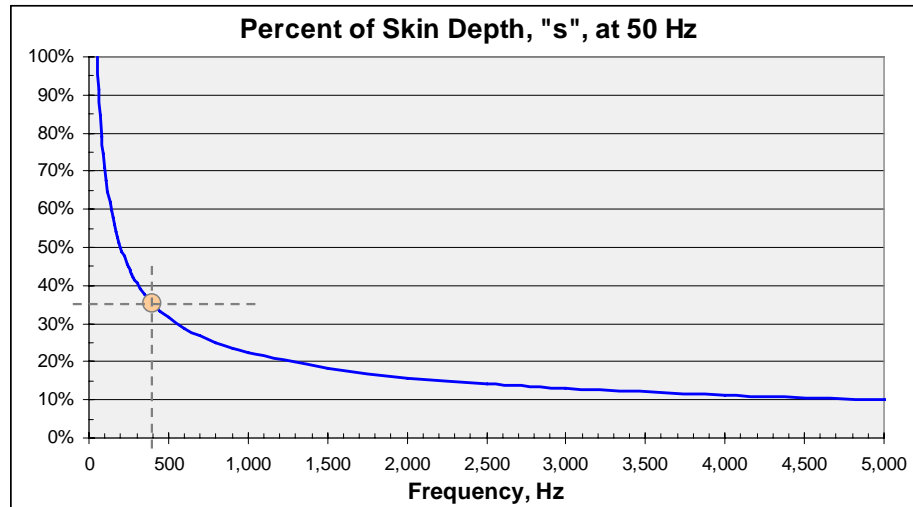
Ferromagnetism, R.M. Bozorth, p.771



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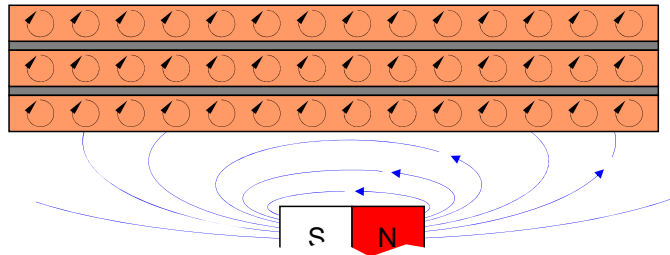
- As frequency increases, eddy currents cannot penetrate as far into the conductive material. This is known as skin effect.
- Bozorth shows the skin depth, “s”, as a function of
 - f = frequency in Hz
 - μ = permeability
 - ρ = resistivity in ohm•cm

2: Eddy Current Skin Depth



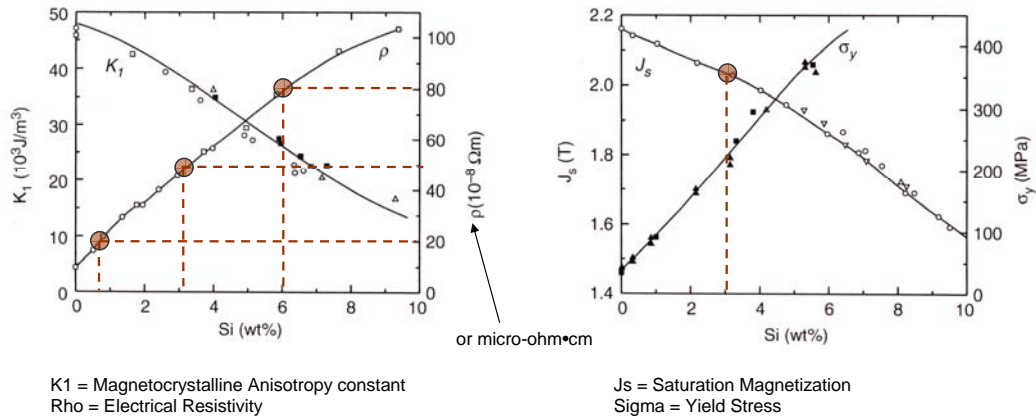
- As frequency increases above 50 Hertz, eddy currents penetrate to a far lesser extent.
- Penetration depth decreases very rapidly when (switching) frequency increases above 50 Hz, reaching at 400 Hz just ~35% of the depth at 50 Hz .

2: Eddy Current Loss



- Since eddy currents are caused by induced voltage in conductive magnetic material. Dividing the material into insulated layers breaks up both the induced voltage and the eddy current, lowering total loss dramatically. The sum of the losses per layer is much less than the loss for the undivided material. Induced voltage is proportional to frequency so there is greater benefit from more and thinner layers as the frequency increases.
- In practical devices then, eddy current loss can be lowered by reducing the thickness of the laminations and including an insulating coating or layer between the laminations.
- In fact, coating technology plays a major role in the ability to use soft magnetic materials at the high frequencies becoming common today.
- A second method to achieve reduction in eddy current loss is use of materials with high resistivity.
- Incidentally, this is why ferrite cores, being a ceramic insulator, are used in very high frequency transformer/inductor applications. However, their saturation magnetization is so low that they are not considered useful for motors and generators.
- Another family of materials, SMC's (Soft Magnetic Composites) are of interest for frequencies above those where thin gauge Fe-Si is useful.

2: Fe-Si Resistivity



Measurement and Characterization of Magnetic Materials, Fausto Fiorillo, p.39

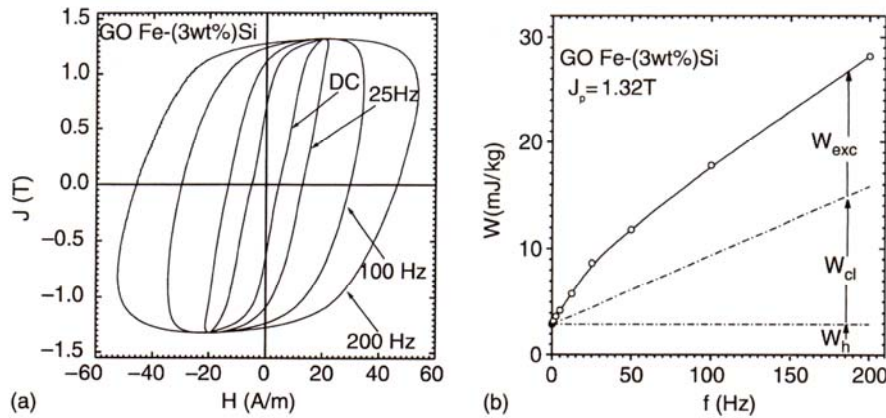


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- The electrical resistivity of 3% Silicon-iron is approximately 50 micro-ohm• cm.
- This is about five times higher than low carbon steel.
- Saturation magnetization is reduced by the presence of silicon, dropping by about 6% with 3% Si. But since the laminations are not driven to saturation in PM motors, this small a drop has negligible affect on normal use.

2: Core Loss Mechanisms

Silicon Steel Core Loss



$$W = W_h + W_{cl} + W_{exc} \quad \text{Where Classical Loss is} \quad W_{cl} = \frac{\pi^2}{6} \frac{\sigma d^2 J_p^2 f}{\delta}$$

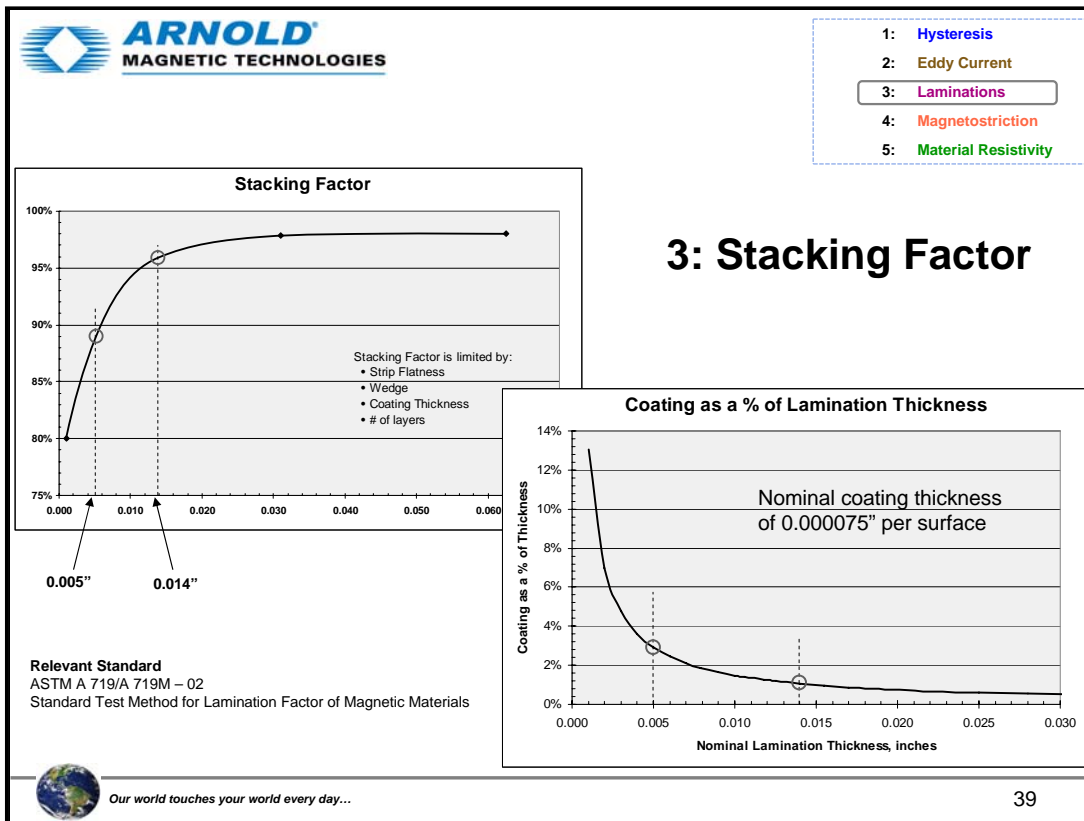
Measurement and Characterization of Magnetic Materials, Fausto Fiorillo, p.31



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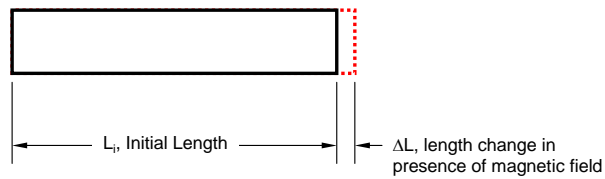
- This chart shows the actual measured core loss of a silicon iron lamination structure and the calculated loss components.
 - Note that the Hysteresis Loss (W_h) is close to constant with frequency.
 - The Classical Loss (W_{cl} , including eddy current loss) is proportional to frequency.
 - The remaining loss is complex in mechanism, and is often referred to as: Anomalous Loss, Residual Loss or Excess Loss. It has not yet been satisfactorily explained though efforts are underway to do so.
 - Lamination thickness in this example is 0.29 mm under sinusoidal time dependence of polarization.
- Delta = density
 - d = lamination thickness
 - Sigma = conductivity
 - J_p = Peak Polarization
 - f = frequency



- We've seen that reducing lamination thickness can reduce core loss due to eddy currents. However, there are several drawbacks that provide practical limits to how thin the laminations may be economically made and used.
 1. **COATING:** First, the coating, although very thin (between 50 and 80 millionths of an inch), separates the laminations. We see in the chart to the right that with 0.005" laminations that the coating represents 3% of the total lamination thickness. Were there no other effects, the stacking factor could be a maximum of only 97%.
 2. **IMPERFECT LAMINATIONS:** Secondly, laminations are not physically perfect. They suffer from wedge and waffling, both contribute to irregular gaps between layers and the actual achievable stacking factor is approximately as shown in the left chart. I say "approximately" as the actual performance will depend greatly upon the physical conformance to a perfect layer.
 3. **QUANTITY HANDLED:** Another issue is that of requirements for punching and stacking larger numbers of laminations to make up the total stack height.
 4. **PUNCH DIFFICULTY:** A 4th issue is that punching of steel becomes more difficult as the laminations become thinner. Thickness to 0.001" are possible, but punch difficulty increases dramatically below lamination thickness of 0.005". At these thin gauges punching is actually a controlled tear. Punch tooling has to be of the highest quality and maintained rigorously.
- The use of thin gauge then depends upon a balance of performance with cost and technical feasibility. Switching frequencies of 400 Hz and higher or the requirement for extremely low core loss make thin gauge NGOs a requisite.

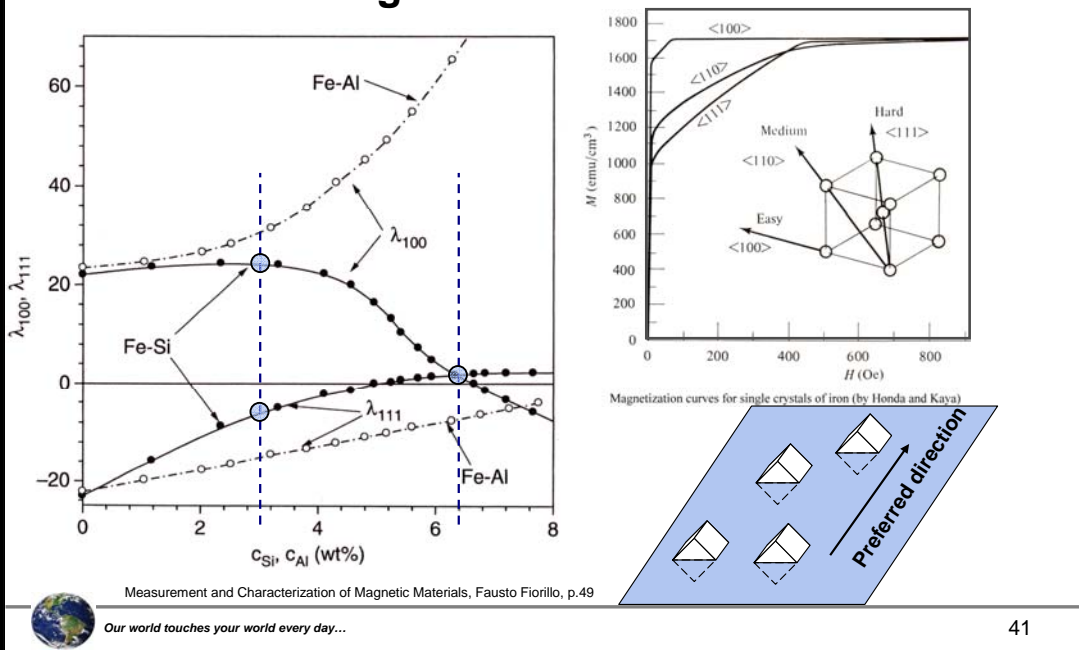
4: Magnetostriction

- Magnetostriction: Dimensional changes due to applied field
- Common in many soft magnetic materials
- Can contribute to core loss



- Ferromagnetic materials experience minor dimension changes when placed in a magnetic field. This effect is called “magnetostriction.”
- The magnitude of these physical changes ($\Delta L / L_i$) are small, typically a few parts per million.
- These dimensional changes absorb energy and contribute to the total core loss.
- Magnetostriction can manifest itself as audible noise, e.g. “transformer hum.”

4: Magnetostriction of Fe-Si



- By the 1940's it was well known that the iron single crystal has a preferred direction along which magnetization is easier than the others – the Goss Structure**. This translates to higher permeability and lower core loss in that given direction, the “cube-on-edge” direction.
- It was recognized that if all the grains in a lamination can be aligned this way, the lamination can be cut to take advantage of this performance enhancement.
- This structure and process were developed to create the preferred orientation in the rolled silicon steel strip. The process involves a combination of cold working and heat treating to produce a strip where most of the metal grains are oriented along the rolling direction.
- While the material is not uniform in all directions, many components such as wound cores and stamped/stacked E cores can be made to maximize the positive aspects of orientation.
- Magnetostriction of 3% Si-Fe varies from about 23 in the easy axis to a negative 6 in the hard axis of orientation - - both numbers $\times 10E-6$.
- At ~6.5% Silicon, magnetostriction reaches a minimum. However, at this level of silicon, the alloy is too hard to roll successfully to thin gauge.
- I have not yet found data for magnetostriction of NGOES.

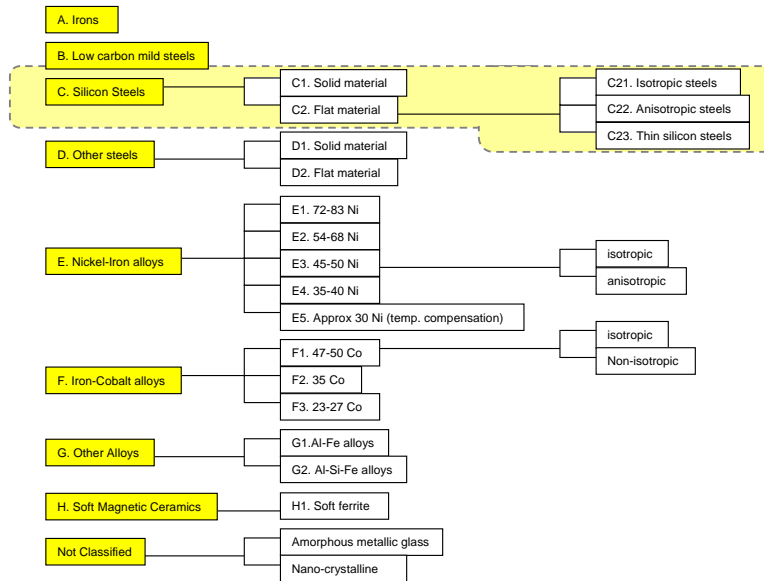
**Norman P. Goss (born [February 04, 1906](#) - died [October 28, 1977](#)) - inventor and researcher from [Cleveland, USA](#). He graduated from [Case Institute of Technology](#) in 1925. He made significant contributions to the field of metals research and in 1935 he patented a method^[1] and published a paper^[2] describing a method of obtaining so-called [grain-oriented electrical steel](#), which has highly [anisotropic](#) magnetic properties. This special "grain-oriented" structure was named after its inventor and it is referred to as the "GOSS structure".

The grain-oriented electrical steel allowed development of highly efficient [electrical machines](#), especially [transformers](#). Today, the [magnetic cores](#) of all high-voltage high-power transformers are made from grain-oriented electrical steel.

- - Wikipedia - -

5: IEC Classifications for Soft Magnetic Materials

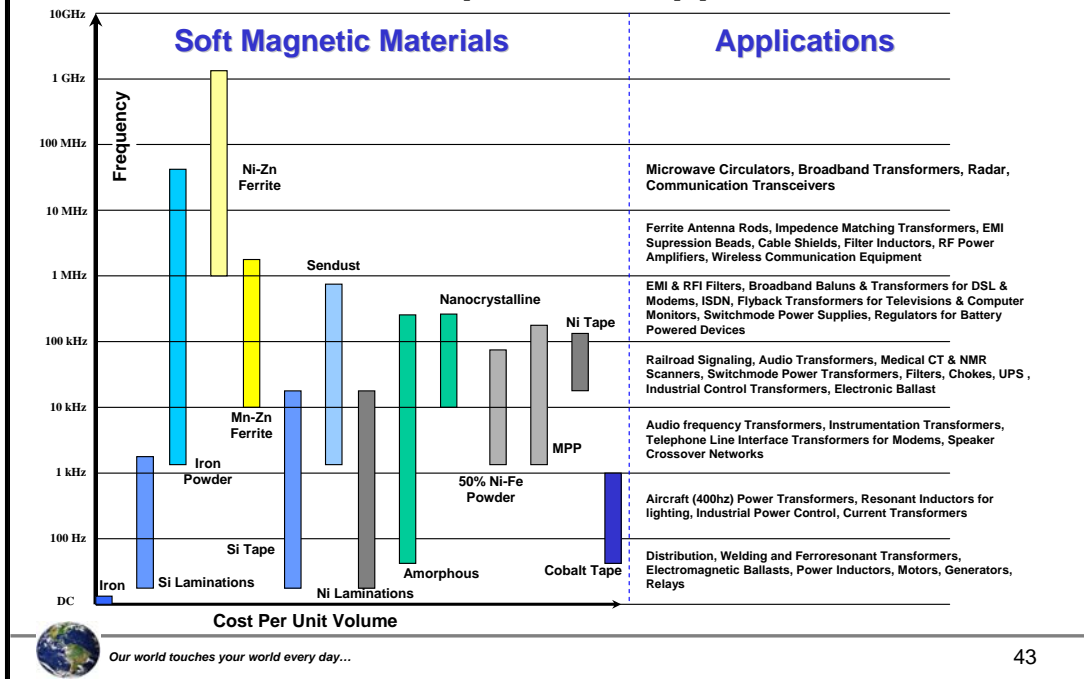
- 1: Hysteresis
- 2: Eddy Current
- 3: Laminations
- 4: Magnetostriction
- 5: Material Resistivity



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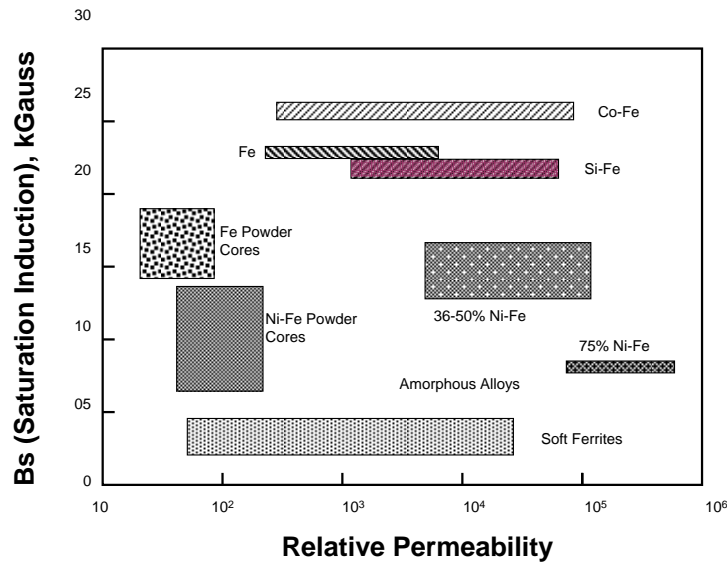
- This is the classification currently adopted by the International Electrotechnical Commission (IEC). It may soon be revised to accommodate new classes of materials such as amorphous and nanocrystalline materials.
- Silicon steels are highlighted...

5: Material Options & Applications



- This chart offers a comparison of soft magnetic materials as a function of cost and usable frequency range.
- Maximum use frequency depends on the operating flux density so the chart should be viewed as a general guide.
- Increasing cost per unit volume is shown from left to right. Performance improvements from a more expensive core material can provide for lower overall system cost.

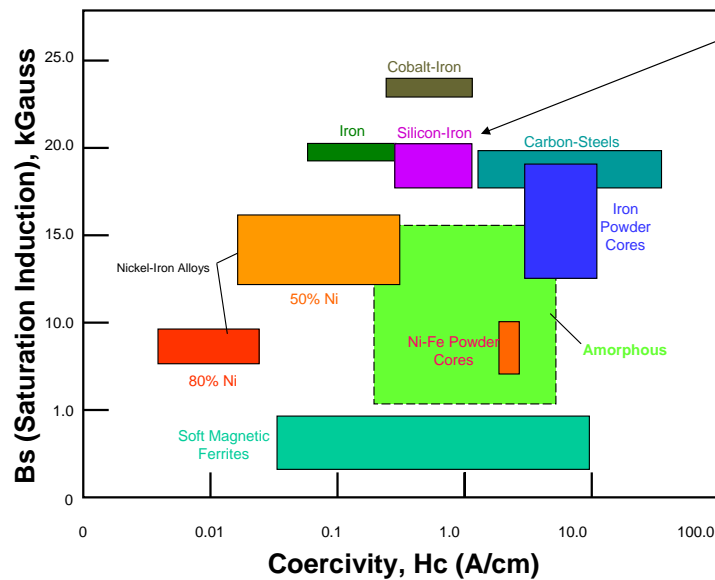
5: Comparing Properties



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- This slide plots permeability versus saturation induction for common soft magnetic materials. Both properties are usually desirable, so the best performing material shown would be the cobalt iron alloys. While the Fe-Co alloys are expensive, they are among of the best performers.
- Only slightly lower in performance is the much less costly Si-Fe material.

5: Comparing Properties (Continued)



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- This is a plot of coercivity, H_c , against saturation induction, B_s (or J_s).
- A high $H_c B_s$ indicates that the material will most likely have high hysteresis core loss.
- From the loss standpoint, the 80% Nickel alloys are desirable.
- For motor and transformer applications, Fe-Si offers the best combination of price and performance.

5: Silicon Steel Designations

The American Iron and Steel Institute type numbers for electrical steel grades consist of the letter M followed by a number. The M stands for magnetic material; the number is representative of the core loss for that grade. At the time the AISI system was adopted, the type number assigned to each grade was approximately 10 times the core loss for 29 gauge material at 15 kG and 60 Hz.

Today, the type numbers do not have the specific association with core loss because electrical steels have been significantly improved, and the core loss guarantees substantially reduced. However, the numbers do indicate not only a specific grade but also the relative core losses of grades within a class.

AK Steel promotional literature: 24-784

IEC	EN	AISI	ASTM	JIS	GOST
404-8-4 -1986	10106 -1995		A677 -1989	2552 -1986	21427 0-75
-	M235-50A	-	-	-	-
250-35-A5	M250-35A	M 15	36F145	35A250	2413
270-35-A5	M270-35A	M 19	36F158	35A270	2412
300-35-A5	M300-35A	M 22	36F168	35A300	2411
330-35-A5	M330-35A	M 36	36F190	-	-
-	M250-50A	-	-	-	-
270-50-A5	M270-50A	-	-	50A270	-
290-50-A5	M290-50A	M 15	47F168	50A290	2413
310-50-A5	M310-50A	M 19	47F174	50A310	2412
330-50-A5	M330-50A	M 27	47F190	-	-
350-50-A5	M350-50A	M 36	47F205	50A350	2411
400-50-A5	M400-50A	M 43	47F230	50A400	2312
470-50-A5	M470-50A	-	47F280	50A470	2311
530-50-A5	M530-50A	M 45	47F305	-	2212
600-50-A5	M600-50A	-	-	50A600	2112
700-50-A5	M700-50A	M 47	47F400	50A700	-
800-50-A5	M800-50A	-	47F450	50A800	2111
-	M940-50A	-	-	-	-
-	M310-65A	-	-	-	-
-	M330-65A	-	-	-	-
350-65-A5	M350-65A	M 19	64F208	-	-
400-65-A5	M400-65A	M 27	64F225	-	-
470-65-A5	M470-65A	M 43	64F270	-	-
530-65-A5	M530-65A	-	-	-	2312
600-65-A5	M600-65A	M 45	64F360	-	2212
700-65-A5	M700-65A	-	64F400	-	2211
800-65-A5	M800-65A	-	-	65A800	2112
-	-	M 47	64F500	-	-
1000-65-A5	M1000-65A	-	64F550	65A1000	-

Key to Metals Task Force & INI International: Silicon Steels and their Applications, www.key-to-steel.com
All of the above specifications have been updated and this list will be updated over the coming months.



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- There is not “1” silicon iron material, but a whole family of materials: oriented and not oriented, different thicknesses and coatings, varying silicon contents, different processing, etc.

Agenda

- Introduction
- Manufacturing Process
- GOES versus NGOES
- Motor Efficiency
- Loss Factors
- NGO Thin Gauge (Arnon)



- Thin gauge ($\leq 0.007''$) Fe-Si is particularly useful for high frequency operation to reduce eddy current loss.
- Oriented product is commonly used in high frequency or burst pulse transformer applications where the benefit of directional properties can be utilized.
- In motors, generators and rotating machinery however, non-oriented Fe-Si is preferred since the field intersects the material at varying angles and benefits from material isotropy.

Applications

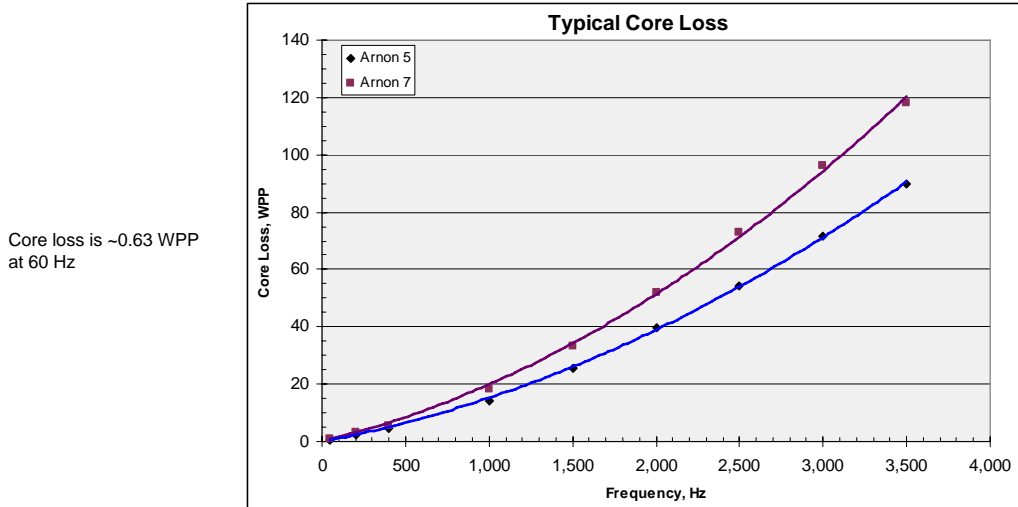
- Thin Gauge (<0.014")
 - Reduced eddy currents at frequencies of 400 Hz and higher
- Silicon-Steel
 - Reduced eddy current losses due to material resistivity
- Non-Grain Oriented
 - Where the direction of magnetic flux is changing
 - Less sensitive to strain than grain oriented

Low loss Arnon materials are especially useful in totally enclosed motor designs and very large devices where heat cannot be easily removed.



- There are three reasons to use Arnon:
 - Thin gauge reduces eddy current loss
 - Silicon steel has higher inherent resistivity
 - Non-oriented magnetic properties improve performance in rotating machinery
- Arnon HcB is less than 0.6 Oersteds, 8 to 15% less than competitive NGOES, resulting in lower hysteresis core loss. (Comparative measurements on same equipment during the same measurement session).
- This lower HcB results from very specific processing conditions during rolling and annealing.

Arnon 5 and 7 Core Loss Non-Grain Oriented, 5 and 7 mil Fe-Si



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- Core loss for the Arnon materials is typically 0.58 and 0.66 WPP for Arnon 5 and Arnon 7 respectively (when tested at 60 Hz).
- Arnon 5 is 0.005” nominal thickness; Arnon 7 is 0.007” nominal.

Large Structure Build-up

Large lamination structures can be fabricated by interleaving laminations - - staggering the overlap regions (step-lap joint). While common in power transformers, it is also employed in rotors and stators.

For example, Arnon 7 is currently being used to build rotors for:

- A 3 meter diameter generator
- Inside-out motors with diameters between 2 and 6 feet.

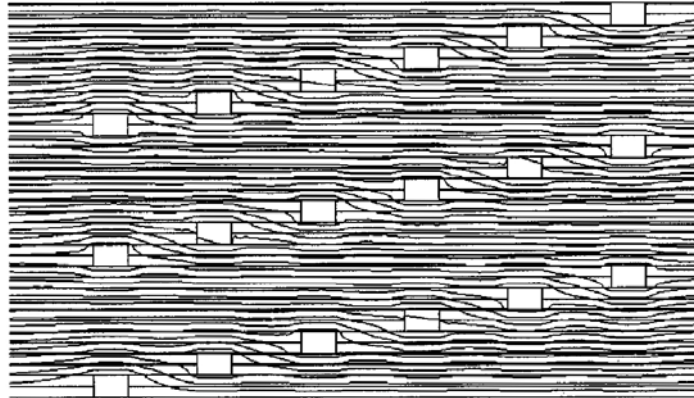


Fig. 6. Magnetic flux density along line 3 of Fig. 2.



- Maximum width for Arnon is ~14". However, larger structures are readily built-up from smaller sections.
- In fact some very large rotating machinery is being constructed from stepped segments.

Very Thin Gauge Fe-Si (Oriented)

Table 1. Recommended Grain Oriented Silicon Steel Thicknesses for Various Operating Frequencies

Frequency	Recommended Thickness	Approximate Induction for 300 mW/cc 18 W/lb, 40 W/kg*
400 Hz	4 mil or 6 mil	15,000 G*
1 kHz	4 mil or 6 mil	10,000 G
2 kHz	2 mil	6,000 G
5 kHz	1 mil	3,000 G

* For reference only. Based on Arnold C-core data records. (Arnold no longer manufactures C-cores). At 400 Hz, magnetizing current limits the maximum flux density.

Table 2. Recommended Grain Oriented Silicon Steel Thicknesses for High-Power Pulse Operating Conditions*

Pulse Width	Recommended Thickness	Pulses per Second
2 to 1000 microseconds	4 mil or 6 mil (D-U, U-I, L-L Laminations)	to 1000
0.25 to 2 microseconds	1 mil or 2 mil (C-core)	to 1000

* For reference only. Based on Arnold C-core data records. (Arnold no longer manufactures C-cores). At 400 Hz, magnetizing current limits the maximum flux density.



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- Arnold also produces grain oriented Fe-Si at 1, 2, 4, and 6 mil, primarily for use in laminated and wound high frequency transformers and chokes.
- However at least one recent design incorporates this material in a segmented stator design - - segmented to allow alignment of the laminations to the applied field.

An Example: Small Motor Comparison

Existing Design

5 HP (Motor + Gearbox)

- Torque Varies
- Speed adjusted with Gearbox, not motor
- Efficiency Varies
- Max Efficiency for Speed range 72%
- Overall Weight: 266lbs



New 5+ HP EVT Motor

(Direct Drive)

- Consistent Torque
- Speed adjusted at motor, precisely
- Efficiency remains consistent
- Max Efficiency for Speed range 97%
- Overall Weight: 200lbs



Courtesy EVT LLC, www.evtllc.com

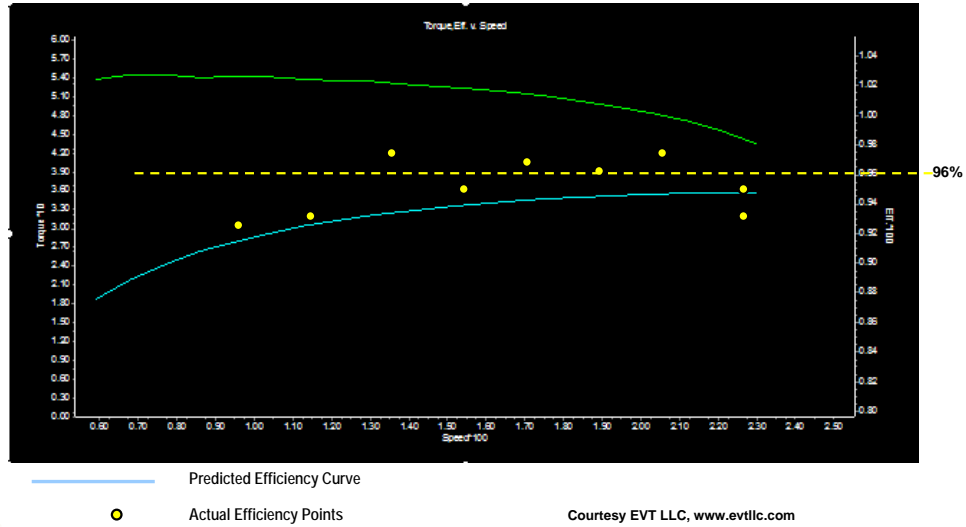


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- The challenge: to replace an open type motor and gear box with a totally sealed motor without gear box while improving on the linearity of torque and raising the efficiency.

Efficiency Curve – Predicted versus Actual Gen 4 Prototype

(Predicted Efficiency curve as illustrated by Motor Development Software, University of Glasgow)



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- Data is from 80 to 230 rpm.
- Torque curve is exceptionally flat.
- Efficiency averages 96% over more than half the speed range and peaks at 97%
- Drive is totally enclosed with no cooling and experiences ~10 °C rise above ambient.

References

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- Hyperphysics (<http://hyperphysics.phy-astr.gsu.edu/hbase/HFframe.html>)
- Wikipedia (www.wikipedia.org)



- All of these were useful, but the three in dark blue were excellent.



Thank you !

