Resources
for Engineers

JOHNSON ELECTRIC
innovating motion

Solenoids

Glossary

A solenoid is a basic, rugged device. Its component parts consist of a coil (to carry current and generate ampere turns), an iron shell or case (to provide a magnetic circuit), and a movable plunger or pole (to act as the working element).

A major objective in the design of a solenoid is to provide an iron path capable of transmitting maximum magnetic flux density with a minimum energy input. Another objective is to get the best relationship between the variable ampere turns and the working flux density in the air gap. When applying a solenoid, it is extremely important to consider the effects of heat, since for a constant voltage application, an increase in coil temperature reduces the work output.

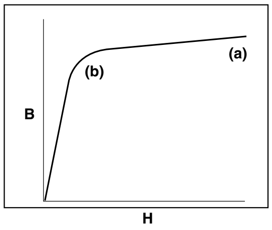
Ambient temperature range, voltage fluctuation, return springs and temperature rise all affect the net output torque/force. For preliminary calculations, we recommend that a 1.5 safety factor be applied to the variables.

Magnetic Flux

Magnetic flux lines are transmitted through the iron shell and the air gap between the shell and the plunger (for linear solenoids) or the armature (for rotary solenoids). An iron path is much more efficient than air, but the air gap is needed to permit movement of the plunger or armature.
The force or torque of a given solenoid is inversely proportional to the square of the distance between the pole faces. The lowest force or torque is generated when the distance is widest/longest; the strongest when the distance is smallest.

Saturation

Saturation of the iron path in a solenoid can be considered in two ways. In the true sense it is point (a) at which the iron ceases to carry any increase in flux. In broader terms, saturation is usually considered as point (b), where the iron begins to saturate.



As the pole pieces are moved together or when input power is increased, the flux density of the magnetic circuit increases until the iron saturates near point (b). Beyond this point any further increase in power only serves to add heat without an appreciable increase in force or torque. By changing the iron path area, the pole shape, or the magnetic circuit material, output torque/force can be increased.

Ampere Turns

The number of copper wire turns, the magnitude of the current, and permeance of the magnetic circuit determine the absolute value of magnetic flux within the solenoid. The permissible temperature rise limits the magnitude of the power input. When using a constant voltage, heat makes the coil less efficient because it reduces the ampere turns and, hence, the flux density and the torque/force output.

Heat

Heat can be dissipated by controlling the air flow, by mounting the solenoid on a surface large enough to dissipate the energy (heat sink), or by resorting to some other cooling method. When space permits, a simple solution is to use a larger solenoid. Heat in a solenoid is a function of power and the time during which power is applied. For continuous duty, hold-in resistor circuits are commonly used to provide higher starting torques/forces than are obtainable at continuous duty rating.

Our stock model standard solenoids are designed to operate in ambient temperatures of -55°C to 80°C. A solenoid operating at the predetermined conditions established in the coil data charts, with the specified heat sink, will have a coil temperature rise of about 80°C (above ambient temperature). Our standard solenoids will withstand 120°C without thermal damage. A special high temperature coil with a 175°C temperature limit, for operation in up to 95°C ambient, is available for rotary and low profile solenoids.

Duty Cycle

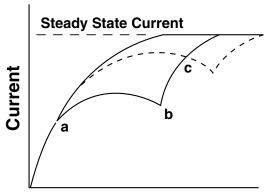
Duty cycle is determined by ON time/(ON + OFF) time. For example, if a solenoid is energized one second out of four seconds, the duty cycle is 1/(1 + 3) = 1/4 or 25%. Duty cycle is the time factor which determines the permissible watts input and the subsequent amount of torque/force and heat. If, for example, a 10-watt input power causes a heat rise of 20°C in 10 seconds, approximately the same temperature rise will result if a power of 100 watts is applied for one second. In terms of duty cycle, a solenoid designed for continuous duty can dissipate ten times the input power at 10% duty.

Maximum ON Time

Solenoids have a maximum ON time for a given duty cycle, wattage and power input. For example, if a solenoid is energized for one second out of four (25% duty cycle), its ON time is one second, which will cause no damage. On the other hand, if the solenoid is energized for 10 minutes out of every 40 minutes at the 25% duty cycle wattage, the duty cycle is still 25%, but its ON time is now 600 seconds. A single pulse of this duration would burn out the solenoid. Ledex DC solenoids are specified with two criteria for maximum ON time: when pulsed repeatedly at the stated watts and duty cycle, and; for a single pulse at the stated watts (with the coil at 20°C ambient temperature).

Operating Speed

The energizing time for a solenoid to complete a given stroke is measured from the beginning of the initial pulse to the seated or energized position. For a given solenoid, this time is dependent upon the load, duty cycle, input power, stroke and temperature range. When a DC voltage is impressed across the solenoid coil, the current will rise to point (a) as shown on the graph below.



This time delay, which occurs prior to the plunger motion, is a function of the inductance and resistance of the coil, and the flux required to move the armature against the load. An increase in the magnetomotive force is created by closing the air

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gap (change in inductance) as the plunger moves through the stroke, causing a dip in the current trace. The cusp at point (b) indicates that the solenoid has completed the stroke. The current trace then begins to rise to a steady state current value which, by Ohm's law, is I = E/R.

The current trace of a solenoid can be observed on an oscilloscope by monitoring the voltage drop across a low resistance, high wattage resistor in series with the solenoid coil.

At point (a) the solenoid has developed sufficient flux to move the load. As the load increases, more time is required to reach point (c), as shown by the phantom current trace. If the load is greater than the output of the solenoid, then the coil will build to a steady state value and a dip in the trace will not occur since the plunger has not moved (top curve).

More time is required to complete the stroke within the force limits of the solenoid as the load increases, the power decreases, or the ambient temperature increases, since these factors affect the net force of the solenoid.

When selecting a solenoid for an application, it is important that these variables be taken into consideration to determine the maximum length of the ON pulse. Once the nominal energizing time has been established, sufficient ON time beyond point (b) should be allotted to compensate for the change in speed due to the maximum load, minimum voltage, and maximum coil temperature.

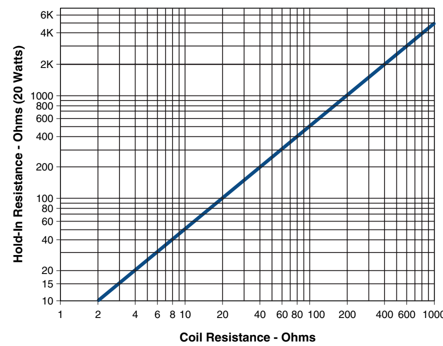
The length of the OFF time or interval between pulses is established by the duty cycle and the input power. If a pulse train is applied for an indefinite period, the interval between pulses should be sufficient to maintain the duty cycle for the input power and wire size tabulated in the coil data tables. Response to a faster pulse rate for intermittent operation is then limited by the temperature rating of the coil and the return speed of the plunger. The return speed can be established by reducing the OFF period until the solenoid energizing trace becomes erratic.

When designing for high speed pulse trains, it is important to consider the type of coil suppression used, and the location of the control circuit.
A diode across the coil may provide satisfactory coil suppression, but it causes a slower collapse of the magnetic field, lengthening the OFF interval required. Ledex high speed coil suppressors use a diode/capacitor/zener diode principle to decrease the drop-out time as well as effectively suppress transients. Placing the control switch to the solenoid on the AC side of a rectifier will have an effect similar to that of using a diode across the coil. If de-energizing speed is critical, the control switch should be located on the DC side of the rectifier and a high speed coil suppressor should be used to provide adequate suppression while allowing fast plunger return speed.

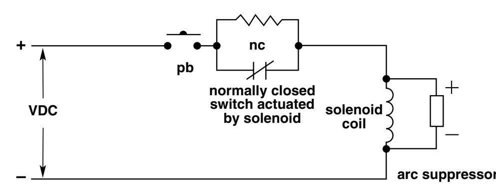
Continuous Duty

For continuous duty applications, or where there is a chance that an operator might close the control switch for a long period, the project engineer has several choices. He can specify a solenoid large enough to provide the torque/force needed on a continuous basis or, if the application permits a higher coil temperature rise, he can specify a smaller solenoid with a high temperature coil to obtain continuous duty operation at a higher power level. He can also use a smaller solenoid and take advantage of the higher torque/force obtainable with an intermittent duty cycle input power. This can be accomplished by using a hold-in circuit to reduce current to a point where torque/force is sufficient to maintain the solenoid in the energized position.

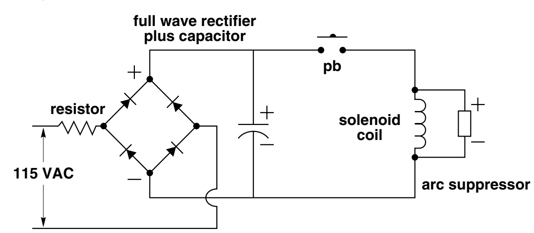
"Hold-in" Resistor Value Estimates



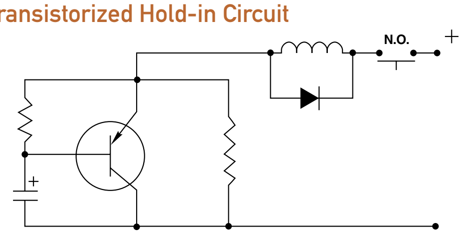
Mechanical Hold-in Resistor Circuit



Capacitor Hold-in Resistor Circuit



Transistorized Hold-in Circuit



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Mechanical Hold-In Resistor Circuit

One of the more common methods to reduce coil current is a normally closed (NC) switch in parallel with a hold-in resistor. When push button (PB) closes the circuit, full voltage is impressed across the solenoid coil, bypassing the resistor through the NC switch. As the solenoid approaches the end of its stroke, a mechanical connection opens the NC contacts, inserting the resistor in series with the coil. This reduces the solenoid voltage to a point where the power input is high enough to allow the solenoid to hold in, and yet stay within its normal heat dissipating range.

Capacitor Hold-In Resistor Circuit

In some cases, a switchless hold-in circuit may be used on 115 VAC applications. This consists of a capacitor which charges to a peak of approximately 150 volts. A resistor in the line ahead of the rectifier controls the hold-in current after the discharged capacitor has supplied the initial high stored energy.

Transistorized Hold-In Circuit

As shown in the transistorized circuit on page H2, when the NO switch is closed, current flows through the base-collector while the capacitor is charging to input voltage. As the base-collector current flows, the emitter-collector circuit allows full power to be impressed across the solenoid coil. The transistor is switched off when the capacitor reaches full charge. Current flow is then through the hold-in resistor and solenoid coil at continuous duty power or less. When using this circuit, it is important that the transistor be on long enough to allow the solenoid to move the load through the complete stroke.

The graph on page L2 is a convenient guide to estimate hold-in resistor values. Because the actual value can vary according to the size of the load to be held, it should be used only as a starting point. Keep in mind that more hold-in current (lower resistance) is needed as the hold-in load increases. To use the graph, locate the coil resistance on the horizontal scale, then read the approximate hold-in resistor value on the vertical scale.

Temperature and Force/Torque Resistance

The force/torque curves and coil data in this catalog are based on the coil being at an ambient temperature of 20°C, and the use of a heat sink comparable to that called out in the notes below each table. When a solenoid is energized, the coil temperature rises. Since resistance varies with temperature, an increase in temperature produces a proportional increase in resistance. Increased resistance reduces the current flow when constant voltage is applied, and decreases the effective ampere turns and torque/force output. For each degree above or below 20°C, the resistance of the coil's copper wire changes by 0.393 percent per degree. A coil temperature rise of 80°C, for example, will increase the coil resistance by a factor of 0.314, which is equal to 80°C x 0.00393/°C. Calculation of resistance at any other temperature (t_2) can be made using the following formula:

$$Rt_2 = R_{20°C}[1 + 0.00393\ (t_2\text{-}20)]$$

Rearrangement of the formula produces a ratio between $R_{20°C}$ and Rt_2 as follows:

$$Rt_2/R_{20°C} = 1 + .00393\ (t_2 - 20) = \text{Resistance Factor (R.F.)}$$

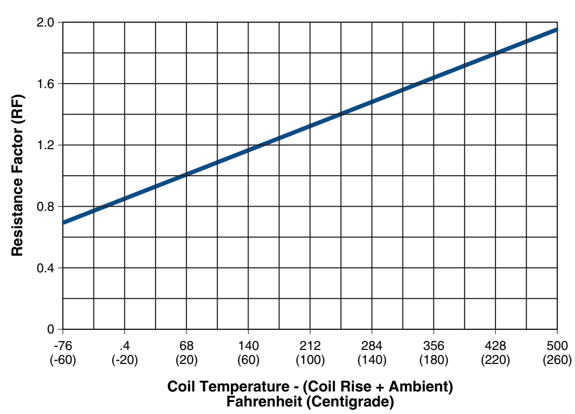
The Resistance Factor of copper wire at temperatures from -60°C (-76°F) to 260°C (500°F) is graphed below.

Once the actual coil temperature (ambient plus rise) is determined, the resistance factor can be determined as follows:

A size 3E, 31 awg coil has a resistance of 31.8 ohms at 20°C. After operating for a prolonged period at 10% duty, the approximate coil rise is 80°C. Added to 20°C, the coil temperature is 100°C. The Resistance Factor graph indicates a 1.3 factor (point where 100°C and diagonal intersect). At 100°C, the resistance of the 31.8 ohm coil is increased by this factor. With a constant voltage applied, the power decrease is proportional to the resistance increase ($P = E^2/R$). The 10% duty power of a size 3 solenoid is 90 watts (at 20°C). The decrease in power at the elevated temperature is calculated by:

$$\frac{\text{90 (Power at 20°C)}}{\text{1.3 (Resistance Factor)}} = 69\text{ W}$$

By interpolating between the 25% and 10% duty cycle curves, the reduction in force due to the 80°C rise can be estimated for a given stroke.



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How to Simulate a Coil Wire Size

If you have a stock model Ledex solenoid, you can simulate performance with a different wire gage by changing the input voltage. A rule of thumb is that, as each wire size changes from one gage to the next, the voltage increases or decreases by the cube root of 2, or a factor of 1.26.

Coil data charts in this catalog are tabulated with voltage values which provide essentially constant ampere turns for each wire size at given duty cycles. A stock model solenoid with a given coil awg can be used to simulate other wire gages under different voltage conditions as follows:

Assume you have a 12-volt power supply and you want to experiment with a size 3 low profile solenoid at continuous duty. In the size 3 coil chart, the closest continuous duty coil is 30 awg (13 volts). You can simulate the exact conditions you would have with a 30 awg coil and a 12 volt input by using a stock model with (1) a 28 awg coil, or (2) a 33 awg coil.

(1) The size 3, 28 awg coil is rated at 8.4 volts, continuous duty. The desired 30 awg coil is 2 gages higher.

$$\frac{12\text{ (your voltage)}}{1.26^2 \text{ (factor for two awg. changes)}} = 7.5$$

7.5 = voltage to simulate 30 awg coil at 12 volts when using stock model size 3 with 28 awg coil.

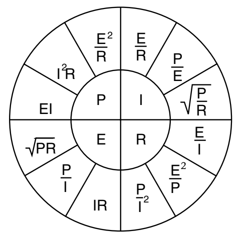
(2) The 33 awg is rated at 26 volts, continuous duty. The desired 30 awg is three gages lower.

12 volts x 1.26^3 = 24

24 = voltage to simulate 30 awg coil at 12 volts when using stock model size 3 with 33 awg coil.

Input Power and Ohm's Law for Direct Current

To understand the relationships of power, current, voltage and resistance, use the chart below.



P = Power (watts)
I = Current (amperes)
E = Electromotive force (volts)
R = Resistance (ohms)

Environmental Considerations

Factors which impact the operation and performance of solenoids include:

- Temperature
- Sand and dust
- Humidity
- Shock and vibration
- Altitude, vacuum and pressure
- Specific application considerations such as paper dust and exposure to certain chemicals

Please consult an application engineer, if any of these factors are prominent in your planned solenoid design.

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Air Gap
The air space between the armature hub and the base or the air space between the stationary and the moveable pole piece.

Ampere Turns
The absolute value of magnetic flux determined by the number of copper wire turns in the coil and the magnitude of the current.
Permissible temperature rise of the coil limits the magnitude of the power input. Heat makes the coil less efficient because it reduces the ampere turns and hence the flux density and the torque or force output

Anchor Plate
The thin formed sheet metal plate fitted over the mounting studs on the base of rotary solenoids to provide containment for the return spring. It has tabs formed up around the circumference which are used to attach the end of the spring and allow adjustment.

Armature Assembly
The assembly consisting of the armature plate, the hub, and the shaft which is the complete moving element in a rotary solenoid.

Armature Plate
The large diameter plate which forms the main rotating element of the solenoid and contains the ball races which convert linear to rotary motion. Made from SAE #1008 or 1010 CRS and case hardened for wearability in the ball races.

Axial Stroke
The amount of longitudinal movement the armature assembly travels as it rotates through its stroke. Value range from 0.022 to 0.100 inches depending on solenoid size and length of stroke.

B-H Curve
The graph of the ratio of flux density to magnetic field intensity. The magnetic field intensity is usually plotted logarithmically.

Bearing Balls
Precision stainless steel balls used in rotary solenoid ball races to provide essentially friction free rotary movement between the armature plate and the case.

Bobbins
Most bobbins are made of nylon 6/6 and meet UL file #E-41938 or E-39806B.

Bobbin Wound Coil
A coil, usually random wound on a spool which maintains the form and shape of the coil and also provides the coil insulation.

Case
The outer shell and main component of the solenoid coil housing. Made of CRS #1008, #1010, 12L14 or 1215 case hardened to 513 on the Vickers scale (RC50) for sizes 0 to 6 (sizes 7 and 8 are not case hardened). The case has the three coined ball races, and is formed from flat stock drawn into a cup (size 7 is machined from bar stock and size 8 is made from tubing stock because of their size and thickness).

Coil
Copper windings providing the electrical element of the solenoid through which current is passed to generate a magnetic field. Coils may be precision wound which allows the maximum amount of copper in the space provided or random wound or bobbin wound.

Coil Arc Suppression
The application of electronic protection devices across switch contacts and coils to reduce the arc caused by interrupting the current flow through an inductive device such as a solenoid. Appropriate coil suppression greatly reduces this arcing.

Coil Resistance
Coil resistance is the property of the coil which impedes the flow of current through it when a voltage is applied. Resistance values are shown in ohms for each solenoid wire awg for a temperature of 20°C. A resistance conversion factor may be used to determine what the resistance would be at other temperatures. This is particularly helpful in determining the effects of temperature on output torque or force. Use the resistance factor chart on page L8 or refer to the Temperature and Force/Torque Resistance section on page L3 for further calculation of resistance at temperatures other than 20°C.

Coining
The process of striking the armature plate or case to form the three ball races on rotary solenoids. This process provides an extremely smooth, mirror-like surface in the ball races.

Dielectric
Dielectric is the resistance between the coil and the case. Minimum dielectric value is 500 VRMS and range up to 1,500 VRMS depending on the solenoid size type and wire gage. Dielectric values are shown for each solenoid in the specifications chart.

Dust Cover
A protective sheet metal cover pressed over the armature plate end of the rotary solenoid to protect the armature and bearing balls from dirt and other contaminants.

Duty Cycle
ON Time/ON+OFF Time = Duty Cycle. Standard duty cycles used in this catalog are 100%, 50%, 25%, 10% and 5%. Other values can be determined by interpolation between any two columns.

Elongated Coils
These coils are 16% longer than standard precision wound rotary solenoid coils, and provide 30% more copper. These units will provide approximately the same torque with less wattage. If the same wattage as the standard precision coils is used, they will provide slightly more torque.

Ending Torque
Torque that a rotary solenoid develops in the last degree or two of stroke.

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End Play
The amount of free axial movement built into a rotary solenoid in the completely de-energized position. This axial movement, normally only a few thousandths of an inch, assures that the solenoid is capable of returning to the completely de-energized position and does not stop before the balls reach the end of their races.

Flux Density
The number of Webers per square meter in a cross section normal to the direction of the flux. This quantity is known as Tesla and given the symbol B. The typical knee in the B-H curve where iron becomes difficult to further magnetize is around 1.6 Tesla.

Flux, Magnetic
The physical manifestation of a condition existing in a medium or material subjected to a magnetizing influence. The quantity is characterized by the fact that an electromotive force is induced in a conductor surrounding the flux during any time there is a change in flux magnitude. A unit of flux is a Weber which is defined as that which being linearly attenuated to zero in 1 second, induces in a surrounding turn, an EMF of 1 volt.

Gross Torque
The starting torque available from a rotary solenoid before subtracting the nominal return spring torque.

Heat Rise
The rise in temperature which results from operating the solenoid at the predetermined conditions established in the coil data charts, with the specified heat sink. Standard solenoids will have a temperature rise of 80°C over ambient.

Heat Sink
The maximum allowable watts for each solenoid are based on an unrestricted flow of air at 20°C with the solenoid mounted on the equivalent heat sink specified for each size. Inadequate heat sink or restricted air flow may result in overheating of the solenoid.

Holding Torque
The torque required to break the armature loose from the energized position while under power. Normally checked under continuous duty operation and after reaching the stabilized operating temperature.

Hub
Part of the armature plate assembly which forms the moving pole face. Made of 12L14 or 1215 CRS. The shaft is pressed into the hub which is staked to the armature plate.

Inductance
An electrical property of solenoids from which can be calculated the current rise time, the stored magnetic energy, the inductive reactance and the impedance. Inductance is an electrical energy storage unit (analogous to capacitance) and is measured in henrys.

Lead Wires
Standard temperature rated coils use PVC insulated stranded lead wire, UL style 1007 rated for 80°C at 300 volts. It also meets CSA type TR-64, 90°C at 600 volts; and MIL-W-16878/2, 105°C at 1000 volts. High temperature coils use Teflon Type E, TFE, and meets MIL-W-16878/4A rated at 200°C at 600 volts.

Lubricant
Standard rotary solenoids are lubricated in the ball races and in the sleeve bearing with Nye Rheolube #719L, a lithium soap-based synthetic hydrocarbon grease with wide temperature capabilities from -54°C to over 93°C. The base oil is compatible with most ester-vulnerable plastics and elastomers. It contains a rust inhibitor and an ultraviolet sensitive dye. Endurance engineered solenoids are lubricated with Shell Alvania #2 which is also a lithium soap-based grease with a temperature range of -29°C to 121°C.

Magnet Wire
100% copper wire, UL-recognized, single film insulation rated at 200°C (NEMA MW 35C) or 155°C (NEMA MW 80C).

Magnetic Field Intensity
The closed loop integral of this quantity is equal to the total current enclosed, as defined by Maxwell's equation. Or, the magnetomotive force per unit length in a magnetic circuit. This quantity is given the symbol H.

Magnetomotive Force
See ampere turns.

Needle Bearing
A bearing used in long life rotary solenoids which is a circle of long needles forming the bearing surface for the shaft.

Net Torque
The starting torque available from the solenoid after subtracting the nominal return spring torque.

PWM (Pulse Width Modulation)
If a solenoid is controlled by a transistor which is signaled from a microprocessor, the PWM can be considered as an alternate means for reducing sizes or saving energy. PWM reduces the effective voltage by pulsing the voltage input. For example, if a solenoid has 12 volts supplied, but at 500 Hz at a 50% duty, the solenoid acts exactly as if it is connected to a 6-volt supply. If the duty cycle is changed to 25%, then the solenoid performs like one hooked to a 3-volt supply. The frequency must be higher than the solenoid can respond to otherwise chatter or humming will occur. Due to the inductive nature of the solenoid coil, the current is smoothed resulting in a constant force. Initially, the microprocessor must leave the transistor on long enough to allow the solenoid to energize. After that point, the microprocessor must alternately issue ON and OFF pulses to the transistor to achieve the appropriate duty cycle.

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Permeability
The ratio of flux density in a given medium to the magnetic field intensity. The symbol used is μ and has the value of 4πE-7 in a vacuum.

Permeance
The ratio of the flux through any given cross section of a given medium (bounded by equipotential surfaces) to the difference in magnetomotive force between the two surfaces.

Plunger
The magnetic moving component of a linear solenoid, typically made from cold, rolled steel.

Precision Wound Coil
A coil whose individual turns have a prescribed pattern which they must follow during the winding process whereby each turn is laid precisely next to the previous turn. This process allows for the maximum amount of copper in the allotted space. Normally carries a ±5% tolerance on coil resistance.

Random Wound Coil
A coil whose turns are allowed to wind randomly in no specific pattern. One turn may overlap another or may lay side by side or even spiral completely across the surface of the coil. Normally carries a ±10% tolerance on resistance

Relative Permeability
The ratio of the flux density in a given medium to that which would be produced in a vacuum with the same magnetizing force. Non-magnetic materials, including air, have a relative permeability of 1, while magnetic materials such as iron, have initial relative permeabilities of around 2,000.

Residual Magnetism
The magnetism which remains in effect on a piece of magnetic material or between two pieces of magnetic material after the electromagnetic field created by the coil has been removed. An air gap is usually maintained between two magnetic poles to minimize the effects of residual magnetism.

Resistance Tolerance
Coil resistance tolerances are generally ±5% for heavier gage wires where precision coil windings are used and ±10% for finer gage wire where random winding processes are used. Tolerances are shown for each solenoid in the individual specification charts.

Return Springs
All standard stock rotary solenoids have scroll type return springs. Values range from 1 oz-in to 1 lb-in depending on the solenoid size. Tolerance on springs are ±20% of the nominal value shown. Return springs are an available feature on any solenoid.

Safety Factor
The ambient temperature range, voltage fluctuation, return springs and temperature rise all affect the net available output torque or force of a solenoid. A 1.5 safety factor should be applied to preliminary calculations of torque or force.

Shaft—Other Solenoids
The main axle of the solenoid which runs from the armature through the base and out the bottom and provides the main bearing. The shaft is also used for external attachment to the solenoid. Normally made of non-magnetic #303 stainless steel. On long-life rotary solenoid models the shaft is made of CRS #12L14 or 1215 which has been case hardened in the bearing area for wear resistance.

Shaft—Tubular Solenoid
The small diameter portion of the plunger assembly of a push-type tubular solenoid which protrudes through the base or stationary pole face and provides push capability; usually made from #303 stainless steel.

Sleeve Bearing
The cylindrical bearing in the base of the solenoid which provides a guide for the shaft. Usually made from phosphor bronze, it can be made of other materials for different applications requiring longer life.

Sleeving
Sleeving used on standard solenoids to insulate the lead wires where they exit the solenoid case is black Vinylite per Mil-I-631B, Type F, subform Ua, Grade C, Class 1, Category 1, and meets UL file #E13565 and E-18459. Sleeving on high temperature coils is Teflon for temperatures up to 200°C continuous and will meet the requirements of AMS 3655 and UL file #E-20344 and E-39513.

Starting Torque
The torque which is produced by a rotary solenoid in the first degree or two of stroke from the de-energized position.

Stator Assembly
That portion of any solenoid which contains the coil, case and base. This portion remains stationary during operation.

Tape
Coil wrapping tape is clear Mylar brand polyester film 0.002" thick which has been slit to the desired width and is used to wrap the coil in an overlapping manner. The film is per Mil-I--631 Type G, Form T_p, Class I, rated for 130°C continuous and meets UL file #E-39505. Coil banding tape is Mylar polyester film, adhesive backed per Mil-I-15126 Type MFT. This tape is used to wrap around the O.D. of the coil one thickness of 0.0025".