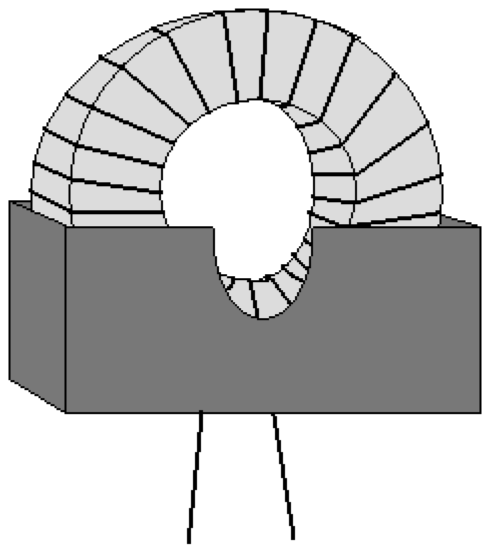
<u>Lecture 17</u> The Toroidal Inductor

Toroids

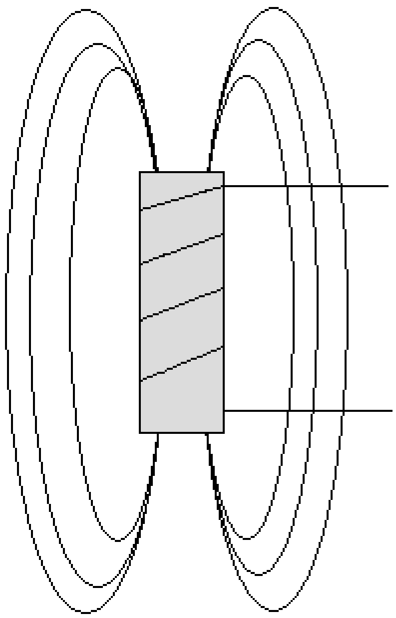
A toroid, simply defined, is a ring or doughnut shaped magnetic device that is widely used to wind RF inductors and transformers. Toroids are usually made of iron or ferrite [1]. They come in various shapes and sizes with widely varying characteristics. When used as cores for inductors, they can typically yield very high Qs. They are self-shielding, compact, and easy to use.



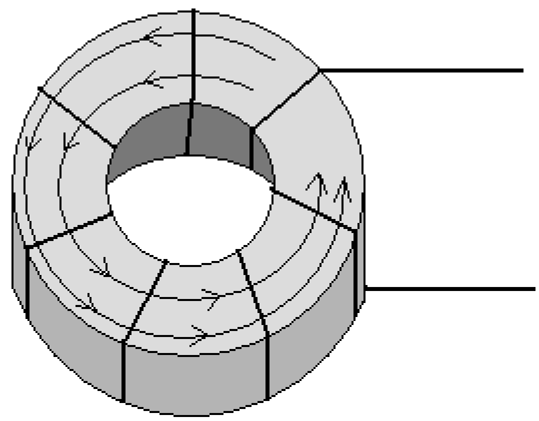
Toroidal Core Inductor

The Q of a toroidal inductor is typically high because the toroid can be made with an extremely high permeability. High permeability cores allow the designer to construct an inductor with a given inductance with fewer turns than is possible with an air core design. For example a given 33μH air core inductor to achieve a high Q would take 90 turns of a very small wire, however, the same toroidal inductor needed only 8 turns to achieve the same Q goal. The toroidal core inductor does require fewer turns for a given inductance that does the air core design. This results in less ac resistance and the Q can be increased dramatically.

The self-shielding properties of a toroid become evident when the figure below is examined. In a typical air core inductor, the magnetic flux lines linking the turns of the inductor take the shape show in the figure. The sketch clearly indicates that the air surrounding the inductor is part of the magnetic flux path. This inductor then tends to radiate the RF signals within. A toroid completely contains the magnetic flux within the material itself, no radiation occurs. (In actual practice some radiation will occur but it is minimized.) This characteristic of toroids eliminates the need for shields around the inductor. Shields not only reduce available space, but they also reduce the Q of the inductor.



Typical inductor



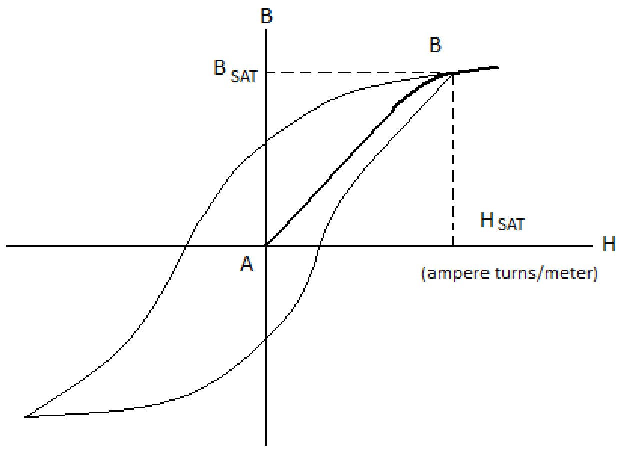
Toroidal Inductor

Core Characteristics

The next figure below is a typical magnetization curve for a magnetic core. The curve simply incdicates the magnetic flux density (B) that occurs in the inductor with a specific magnetic field intensity (H) applied. As the magnetic field intensity is increased from zero, the magnetic density that links the turns of the inductor increases quite linearly. The ratio of the magnetic flux density to the magnetic field density is called the permeability of the material.

$$\mu = \frac{B}{H} \text{ (webers/ampere-turn)}$$

Thus, the permeability of a material is simply a measure of how well it transforms an electrical excitation into a magnetic flux. The better it is at this transformation, the higher the permeability.



Magnetization Curve for a Typical Core

Initially the magnetization curve is linear. It is during this linear portion of the curve that permeablility is usually specified and it is sometimes called initial permeability (μ_i) in various core literature. As the electrical excitation increases a point is reached at which the magnetic flux intensity does not continue to increase at the same rate as the excitation and the slope of the curve begins to decrease. Any further increase in excitation may cause *saturation* to occur. H_{sat} is the excitation point above which no further increase in magnetic flux density occurs (B_{sat}). The incremental permeability above this point is the same as air. In RF circuit applications, we keep the excitation small enough to maintain linear operation.

B_{sat} varies from core to core, depending upon the size and shape of the material. It is necessary to read and understand the manufacturer's literature that describes the particular core you are using. Once B_{sat} is known for the core, it is a simple matter to determine whether or not its use in a particular circuit application will cause it to saturate. The operational flux density (B_{op}) of the core is give by the equation:

$$B_{OP} = \frac{E \times 10^8}{(4.44) f N A_e}$$

where:

B_{OP} = the magnetic flux density in gauss
E = the maximum rms voltage across the inductor in volts
f = frequency in Hertz
N = number of turns
A_e = the effective cross sectional area of the core in cm^2

If the calculated B_{OP} for a particular application is less than the published specification for B_{SAT}, then the core will not saturate and its operation will be somewhat linear.

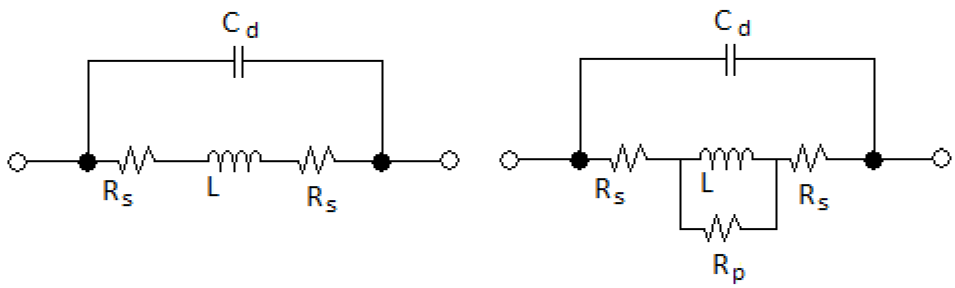
Another characteristic of magnetic cores that is very important to understand is that of internal loss. The careless addition of a magnetic core to an air-core inductor could possibly reduce the Q of the inductor.

Given the equivalent circuit of an air core inductor and a ferrite core is given below. The Q of the inductor is given by:

$$Q = X_L/R_S \text{ (air core)}$$

where: $X_L = \omega L$

R_S = the resistance of the windings



Air Core **Magnetic Core**

If we add a magnetic core to the inductor, we have added resistance R_P to represent the losses which take place in the core itself. These losses are in the form of *hysteresis*. Hysteresis is the power lost in the core due to the realignment of the magnetic particles within the material with changes in excitation, and the eddy currents that flow in the core due to the voltages induced within. These two types of internal loss (which are inherent to some degree in every magnetic core and are unavoidable) combine to reduce the efficiency of the inductor and increase its loss.

But what about the new Q for the magnetic core inductor? This is a question that is not easily answered. When a magnetic core is inserted into an existing inductor, the value of the inductance is increased. At any given frequency, its reactance increases proportionally. The question that must be answered to determine the Q of the inductor is: By what factors did the inductance and loss increase? If by adding a toroidal core, the inductance was increased by a factor of two and its total loss was also increased by a factor of two, the Q would remain unchanged. If the total coil less were increased to four times its previous value while only doubling the inductance, the Q of the inductor would be reduced by a factor of two.

We must also keep in mind that the additional loss introduced by the core is not constant, but varies (usually increases) with frequency. The designer must have a complete set of manufacturer's data sheets for every core he is working with.

Toroid manufactures typically publish data sheets which contain all the information needed to design inductors and transformers with a particular core. In most cases each manufacturer presents the information in a unique manner and care must be taken in order to extract the information that is needed without error, and in a form that can be used is the design process.

Powdered Iron vs. Ferrite

There are no hard and fast rules governing the use of ferrite cores versus powdered iron cores in RF circuit design. In many instances either core could be used without much change in performance of the circuit. There are, however, special applications in which one core might outperform another.

Powdered iron cores can typically handle more RF power without saturation or damage than the same size ferrite core. For example, ferrite, if driven with a large amount of RF power, tends to retain its magnetism permanently. This ruins the core by changing its permeability permanently. Powdered iron if overdriven will eventually return to its initial permeability (μ_i). In any application where high RF power levels are involved, iron cores might be the best choice. In general, powdered iron cores tend to yield higher Q inductors at higher frequencies than an equivalent size ferrite core. This is due to the inherent core characteristics of powdered iron cores which produce less internal loss than ferrite cores. This characteristic of powdered iron makes it very useful in narrow band or tuned-circuit applications.

At very low frequencies, or in broadband circuits which span the spectrum from VLF up through VHF, ferrite seems to be the general choice. For a given core size, ferrite cores have a much higher permeability. The higher permeability is needed at the low end of the frequency range where, for a given inductance, fewer windings would be needed with the ferrite core. This brings up another point. Since ferrite cores have a higher permeability than the same size powdered iron core, a coil of a given inductance can usually be wound on a smaller ferrite core and with fewer turns.

Toroidal Inductor Design

For a toroidal inductor operating on the linear (non-saturating) portion of its magnetization curve, its inductance is given by the following equation:

$$L = \frac{0.4\pi N^2 \mu_i A_C \times 10^{-2}}{l_e}$$

where: L = the inductance in nano-henries

N = the number of turns

μ_i = initial permeability

A_C = the cross sectional area of the core in cm2

l_e = the effective length of the core in cm

In order to make calculations easier, most manufacturers have combined μ_i, A_C, l_e, and other constants for a given core into a single quantity called the *inductance index*, A_L. The inductance index relates the inductance to the number of turns for a particular core. This simplification reduces the equation for toroidal inductor design to:

$$L = N^2 A_L \text{ nano-henries}$$

The number of turns to be wound on a given core for a specific inductance is given by:

$$N = \sqrt{\frac{L}{A_L}}$$

Table 17.1 Toroidal Core Symbols and Definitions

Symbol	Description	Units
A_C	Available cross sectional area. The area perpendicular to the wire.	cm^2
A_e	Effective area of the core. Cross sectional area that an equivalent gapless core would have.	cm^2
A_L	Inductive index. (relates the inductance to the number of turns for a particular core)	$nH/turn^2$
B_{SAT}	Saturation flux density of the core	Gauss
B_{OP}	Operating flux density of the core	Guass
l_e	Effective length of the flux path	Cm
μ_i	Initial permeability. The effective permeability of the core at low excitation in the linear region.	numeric

Table 17.2 Powdered Iron Materials

Material	Application/Classification
Carbonyl C	A medium-Q powered iron material at 150 kHz. A high cost material for AM tuning applications and low-frequency IF transformers
Carbonyl E	The most widely used of all powdered iron materials. Offers high-Q and medium permeability in the 1 MHz to 30 MHz frequency range. A medium cost material for use in IF transformers, antenna coils, and general purpose designs.
Carbonyl J	A high-Q powdered iron material at 40 to 100 MHz, with a medium permeablility. A high cost material for FM and TV applications.
Carbonyl SF	Similar to Carbonyl E, but with a better Q up through 50 MHz. Cost more than Carbonyl E.
Carbonyl TH	A powdered iron material with a higher Q tha Carbonyl E up to 30 MHz, but less than carbonyl SF. Higher cost than Carbonyl E.
Carbonyl W	The highest cost powdered iron material. Offers a high Q to 100 MHz, with medium permeability.
Carbonyl HP	Excellent stability and a good Q for lower frequency operation to 50 KHz. A powdered iron material
CarbonylGS6	For commercial broadcast frequencies. Offers good stability and a high Q.
IRN-8	A synthetic oxide hydrogen reduced material with a good Q from 50 to 150 MHz. Medium priced for use in FM and TV applications.

1. Any of several magnetic substances that consist of an iron oxide combined with one or more metals (as manganese, nickel,, or zinc), have high magnetic permeability and high electrical resistivity.

Equation of interest:

$$Q = \frac{R_p/N^2}{X_p/N^2} = \frac{R_p}{X^p}$$

Example 1

Problem:

Using the data given in the first data sheet, design a toroidal inductor with an inductance of 50 µH. What is the largest AWG wire that we could possibly use while still maintaining a single-layer widning? The frequency of interest is 100 MHz.

Solution:

There are numerous possibilities in this particular design since no constraints were placed on us. The first data sheet for the Indiana General Series of ferrite toroidal cores. This type of core would normally be used in broadband or low-Q transformer applications rather than in a narrow-band tuned circuits.

The mechanical specifications for this series of cores indicate a fairly typical size for toroids used in small-signal RF circuit design. The largest core for this series is just under a quarter of an inch in diameter. Since no size constraints were placed on us in the problem statement, let’s use the AA-03 which has an outside diameter of 0.0230 inch. This will allow us to use a larger diameter wire to wind the inductor.

The published value for A_L for the given core is 495 nH/turn^2. Using the equation for N given in the lecture notes, the number of turns for this core is:

$$N = \sqrt{\frac{50{,}000 \text{ nH}}{495 \text{ nH/turn}^2}} = 10 \text{ turns}$$

Note that the inductance of 50 µH was replaced with its equivalent of 50,000 nH. The next step is to determine the largest diameter wire that can be used to wind the inductor while still maintaining a single-layer winding. In some cases, the data supplied by the manufacturer will include this type of winding information. In those cases, the designer need only look in a table to determine the maximum wire size that can be used. In our case, this information was not given, so a calculation must be made. The inner radius (r_1) of the toroid is the limiting factor in determining the maximum number of turns for a given wire diameter.

The maximum diameter wire for a given number of turns can be found by:

$$d = \frac{2\pi r_1}{N+\pi}$$

where:

d = the diameter of the wire in inches
r_1 = the inner radius of the core in inches
N = the number of turns

From the data sheet $r_1 = d_2 = 0.120$ inch
As a rule of thumb, taking into account the insulation thickness variation among manufacturers, it is best to add some cushion. Take 90% of the calculated value, or 25.82 mils. The largest diameter wire used would be 22 AWG.

Example 2
Problem:
Using information provided in data sheet 2, design a high Q (Q > 80), 300 nH, toroidal inductor for use at a 100 MHz. Due to PC board space, the toroid may not be any larger than 0.3 inch in diameter.

Solution:
The second data sheet is an excerpt from an Amidon Associates iron powder toroidal core data sheet. The recommended operating frequencies for various materials are shown in the Iron-Powder vs. Frequency Range graph. Either material No. 12 or material No. 10 seems to be well suited for operation at 100 MHz. Elsewhere on the data sheet, material No. 12 is listed an IRN-8. (IRN-8 is described in table 17.2 of the lecture notes. Material No. 10 is not described so choose material No. 12.

Under the heading of Iron-Powder Toroidal Cores, the data sheet list the physical dimensions of the toroids along with the vaue of A_L for each. Note that this particular company chooses to specify A_L in μH/100 turns rather than μH/100 turns^2. The conversion factor between their value of A_L and A_L in nH/turn^2 is to divide their value of A_L by 10. The T-8—12 core with an AL of 22 μH/100 turns is equal to 2.2 nH/turn^2.

The data sheet list a set of Q-curves for the cores listed in the preceding charts. All the curves shown indicate Qs that are greater than 80 at 100 MHz.

Choose the largest core available that will fit in the allotted PC board area. The core you should have chosen is the number T-25-12, with an outer diameter of 0.255 inch.

A_L = 12 μH/100 t

A_L = 1.2 μH/100 t

Using the equation we have for N.

$$N = \sqrt{\frac{L}{A_L}} = \sqrt{\frac{300}{1.2}} = 15.81 \; or \; 16 \text{ turns}$$

The chart of Number of turns vs. Wire size and Core Size on the data sheet indicates that for a T-25 size core, the largest wire size we can use in No. 28 AWG to wind this core.

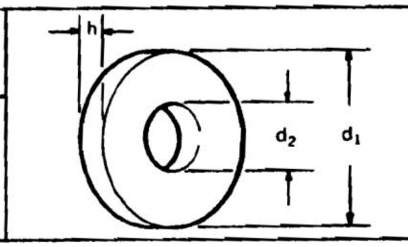
BROAD BAND-RATED FERRAMIC COMPONENTS

Nom. μ_i 2500

- Values measured at 100 KHz, T = 25°C.
- Temperature Coefficient (TC) = 0 to +0.75% /°C max., -40 to +70°C.
- Disaccommodation (D) = 3.0% max., 10-100 min., 25°C.
- Hysteresis Core Constant (η_i) measured at 20 KHz to 30 gauss (3 milli Tesla).
- For mm dimensions and core constants, see page 30.

MECHANICAL SPECIFICATIONS

	PART NUMBER				TOL	UNITS
	AA-01	AA-02	AA-03	AA-04		
d_1	0.135	0.155	0.230	0.100	±0.005	in.
d_2	0.065	0.088	0.120	0.050	±0.005	in.
h	0.055	0.051	0.060	0.050	±0.005	in.

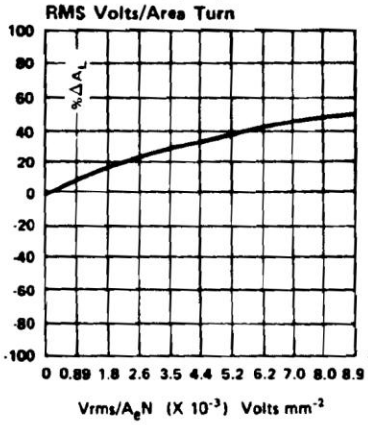


ELECTRICAL SPECIFICATIONS

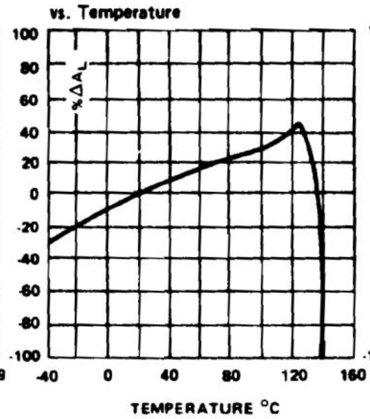
	PART NUMBER				TOL	UNITS
	AA-01	AA-02	AA-03	AA-04		
A_L	510	365	495	440	±20%	nH/turn²
X_p/N^2	0.320	0.229	0.310	0.276	±20%	ohm/turn²
R_p/N^2	10.4	7.5	10.0	8.9	min.	ohm/turn²
Q	54	54	54	54	min.	
V_{rms}	7.9	7.1	13.6	5.1	max.	mv
η_i	1,480	1,400	0,920	2,150	max.	$VSA^{-2}H^{-3/2}$

TYPICAL CHARACTERISTIC CURVES — Part Numbers: AA-01, AA-02, AA-03 and AA-04

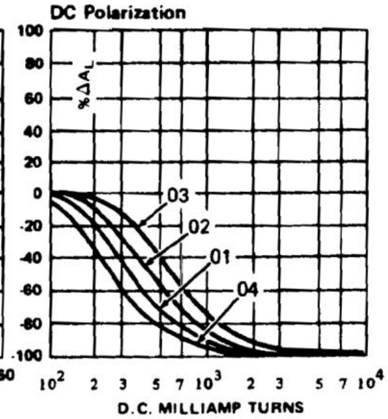
Inductance Factor vs. RMS Volts/Area Turn



Inductance Factor vs. Temperature



Inductance Factor vs. DC Polarization

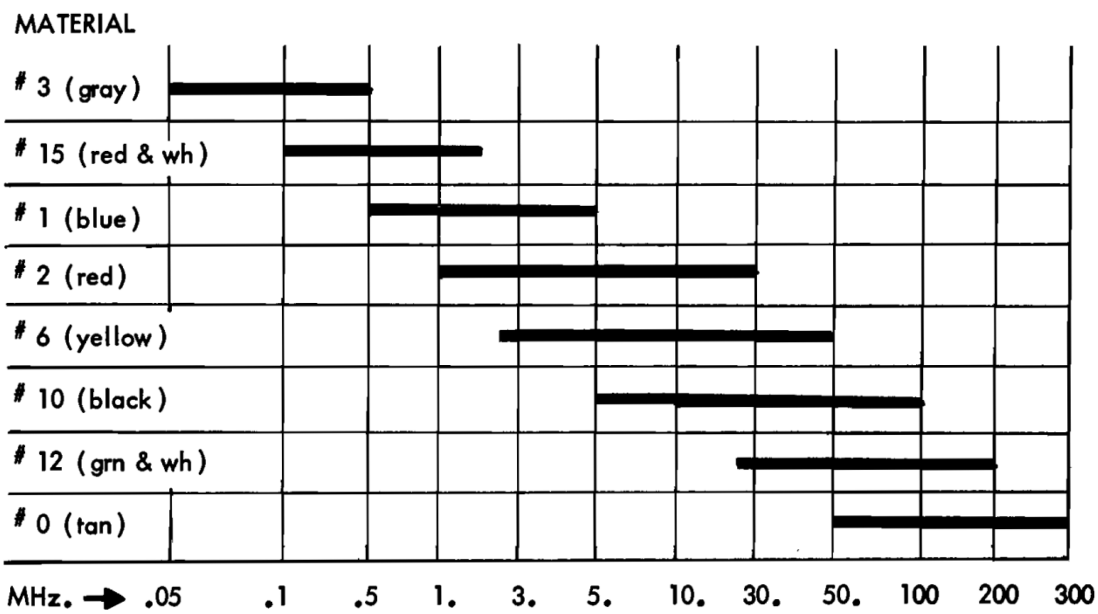


IRON-POWDER TOROIDAL CORES

Core size	Outer Diam. (in)	Inner Diam. (in)	Height (in)	Cross Sect. Area $(cm)^2$	Mean Length (cm)
	PHYSICAL DIMENSIONS				
T-225A - -	2.250	1.400	1.000	2.742	14.56
T-225 - -	2.250	1.400	.550	1.508	14.56
T-200 - -	2.000	1.250	.550	1.330	12.97
T-184 - -	1.840	.960	.710	2.040	11.12
T-157 - -	1.570	.950	.570	1.140	10.05
T-130 - -	1.300	.780	.437	.930	8.29
T-106 - -	1.060	.560	.437	.706	6.47
T- 94 - -	.942	.560	.312	.385	6.00
T- 80 - -	.795	.495	.250	.242	5.15
T- 68 - -	.690	.370	.190	.196	4.24
T- 50 - -	.500	.303	.190	.121	3.20
T- 44 - -	.440	.229	.159	.107	2.67
T- 37 - -	.375	.204	.128	.070	2.32
T- 30 - -	.307	.150	.128	.065	1.83
T- 25 - -	.255	.120	.096	.042	1.50
T- 20 - -	.200	.088	.070	.034	1.15
T- 16 - -	.160	.078	.060	.016	0.75
T- 12 - -	.120	.062	.050	.010	0.74

IRON - POWDER MATERIAL vs. FREQUENCY RANGE

Higher Q will be obtained in the upper portion of a materials frequency range when smaller cores are used. Likewise, in the lower portion of a materials frequency range, higher Q can be achieved when using the larger cores.



IRON-POWDER TOROIDAL CORES

FOR RESONANT CIRCUITS

MATERIAL # 0 permeability 1 50 MHz to 300 MHz Tan

Core number	Outer diam. (in.)	Inner diam. (in.)	Height (in.)	A_L value uh / 100 t
T-130-0	1.300	.780	.437	15.0
T-106-0	1.060	.560	.437	19.2
T- 94-0	.942	.560	.312	10.6
T- 80-0	.795	.495	.250	8.5
T- 68-0	.690	.370	.190	7.5
T- 50-0	.500	.303	.190	6.4
T- 44-0	.440	.229	.159	6.5
T- 37-0	.375	.205	.128	4.9
T- 30-0	.307	.151	.128	6.0
T- 25-0	.255	.120	.096	4.5
T- 20-0	.200	.088	.067	3.5
T- 16-0	.160	.078	.060	3.0
T- 12-0	.125	.062	.050	3.0

MATERIAL # 12 permeability 3 20 MHz to 200 MHz Green & White

Core number	Outer diam. (in.)	Inner diam. (in.)	Height (in.)	A_L value uh / 100 t
T-80-12	.795	.495	.250	22
T-68-12	.690	.370	.190	21
T-50-12	.500	.300	.190	18
T-44-12	.440	.229	.159	18
T-37-12	.375	.205	.128	15
T-30-12	.307	.151	.128	16
T-25-12	.255	.120	.096	12
T-20-12	.200	.088	.067	10
T-16-12	.160	.078	.060	8
T-12-12	.125	.062	.050	7

Key to part numbers for :
IRON POWDER TOROIDAL CORES

T ------- 200 -------- 2

Toroid — Outer diameter — Material

$$\text{Number of turns} = 100\sqrt{\frac{\text{desired inductance (uh)}}{A_L \text{ value (uh per 100 turns)}}}$$

A_L values ± 5%

IRON-POWDER TOROIDAL CORES

FOR RESONANT CIRCUITS

MATERIAL # 10	permeability 6	10 MHz to 100 MHz		Black
Core number	Outer diam. (in.)	Inner diam. (in.)	Height (in.)	A_L value uh / 100 t
T-94-10	.942	.560	.312	58
T-80-10	.795	.495	.250	32
T-68-10	.690	.370	.190	32
T-50-10	.500	.303	.190	31
T-44-10	.440	.229	.159	33
T-37-10	.375	.205	.128	25
T-30-10	.307	.151	.128	25
T-25-10	.255	.120	.096	19
T-20-10	.200	.088	.067	16
T-16-10	.160	.078	.060	13
T-12-10	.125	.062	.050	12

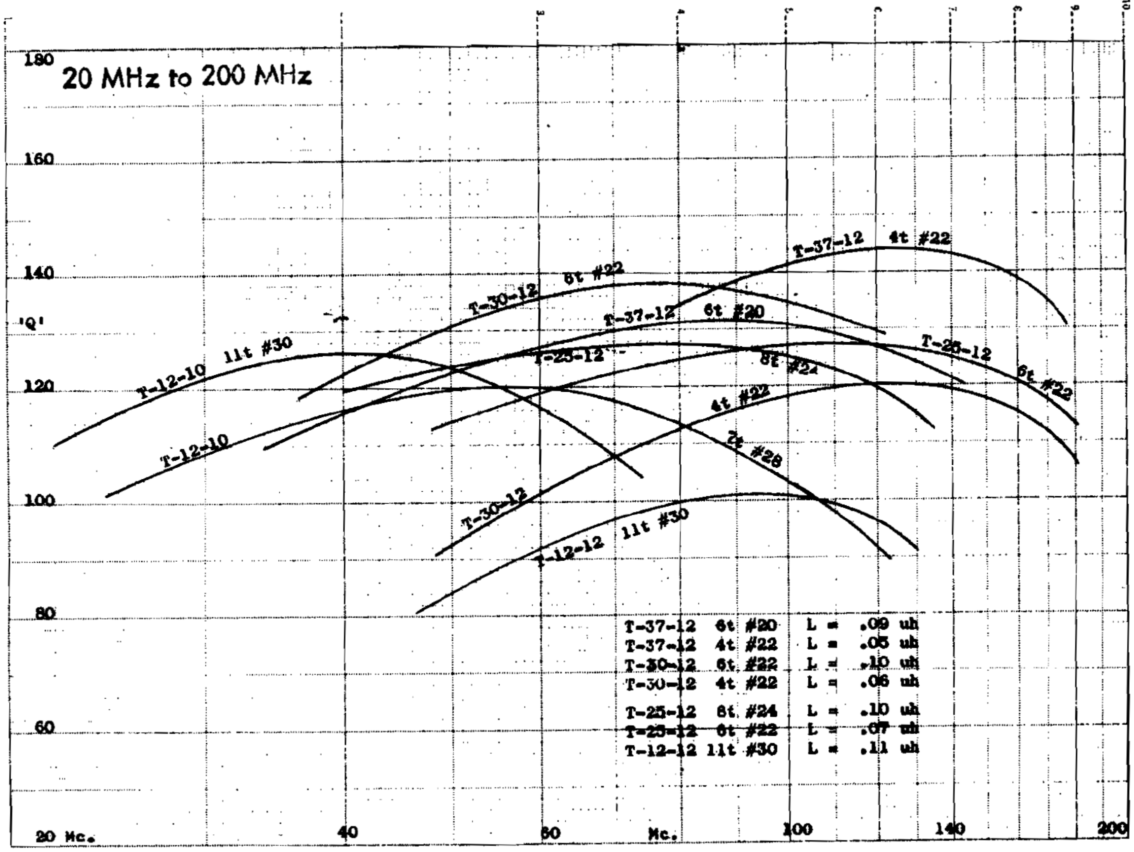
NUMBER OF TURNS vs. WIRE SIZE and CORE SIZE

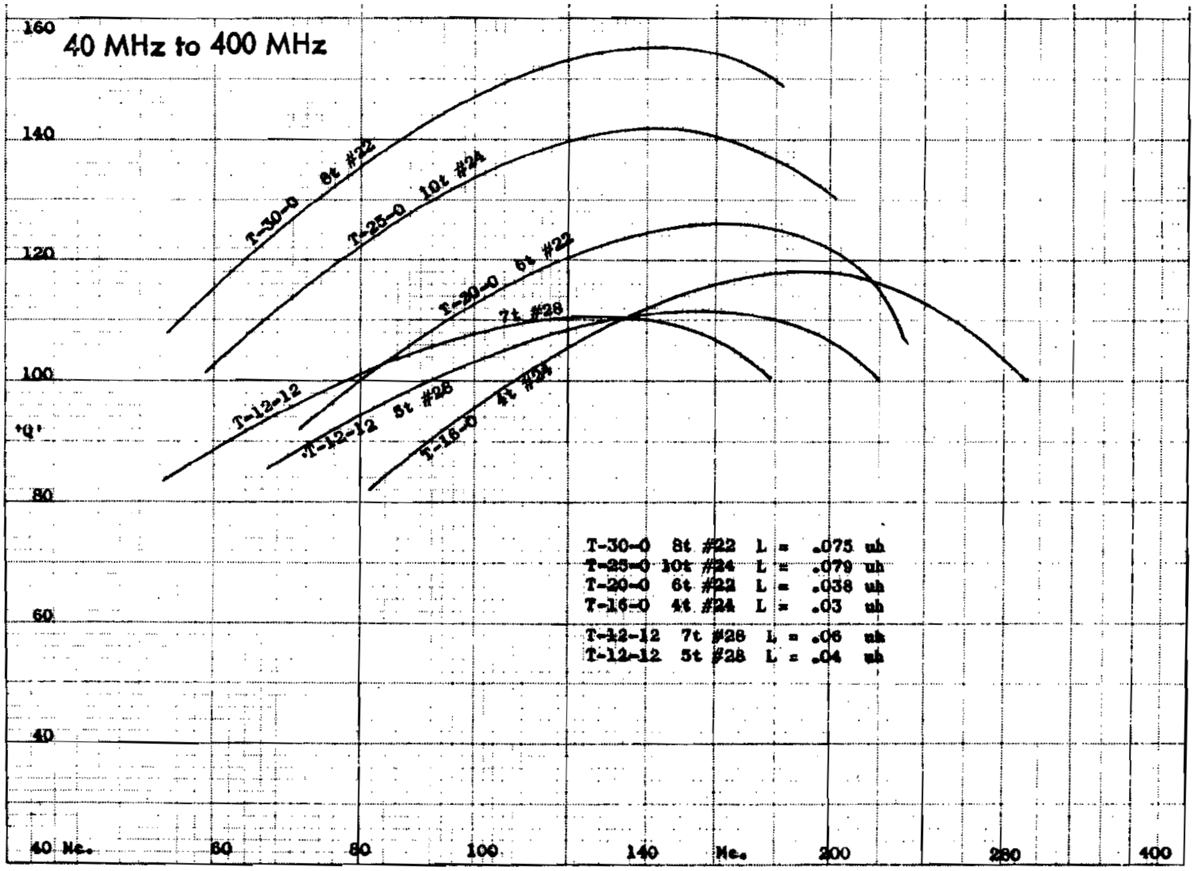
Approximate number of turns of wire - single layer wound - single insulation

Core Size	40	38	36	34	32	30	wire 28	size 26	24	22	20	18	16	14	12	10
T-12	47	37	29	21	15	11	8	5	4	2	1	1	1	0	0	0
T-16	63	49	38	29	21	16	11	8	5	3	3	1	1	1	0	0
T-20	72	56	43	33	25	18	14	9	6	5	4	3	1	1	1	0
T-25	101	79	62	48	37	28	21	15	11	7	5	4	3	1	1	1
T-30	129	101	79	62	48	37	28	21	15	11	7	5	4	3	1	1
T-37	177	140	110	87	67	53	41	31	23	17	12	9	7	5	3	1
T-44	199	157	124	97	76	60	46	35	27	20	15	10	7	6	5	3
T-50	265	210	166	131	103	81	63	49	37	28	21	16	11	8	6	5
T-68	325	257	205	162	127	101	79	61	47	36	28	21	15	11	9	7
T-80	438	347	276	219	172	137	108	84	66	51	39	30	23	17	12	8
T-94	496	393	313	248	195	156	123	96	75	58	45	35	27	20	14	10
T-106	496	393	313	248	195	156	123	96	75	58	45	35	27	20	14	10
T-130	693	550	439	348	275	220	173	137	107	83	66	51	40	30	23	17
T-157	846	672	536	426	336	270	213	168	132	104	82	64	50	38	29	22
T-184	846	672	536	426	336	270	213	168	132	104	82	64	50	38	29	22
T-200	1115	886	707	562	445	357	282	223	176	139	109	86	68	53	41	31
T-225	1250	993	793	631	499	400	317	250	198	156	123	98	77	60	46	36

Q—CURVES

IRON-POWDER TOROIDAL CORES





40 MHz to 400 MHz
160
140
120
100
'Q'
80
60
40
T-30-0 8t #22
T-25-0 10t #24
T-20-0 6t #22
7t #28
T-12-12
T-12-12 5t #28
T-16-0 4t #24
T-30-0 8t #22 L = .075 uh
T-25-0 10t #24 L = .079 uh
T-20-0 6t #22 L = .038 uh
T-16-0 4t #24 L = .03 uh
T-12-12 7t #28 L = .06 uh
T-12-12 5t #28 L = .04 uh
40 Mc.
60
80
100
140
Mc.
200
280
400