Magnetic Devices

INTRODUCTION

Magnetic devices addressed here include transformers, inductors, coils, and RF chokes. Although there are several types of magnetic devices, many properties and failure mechanisms are common; therefore, for the purpose of derating, requirements are subdivided based on frequency. Two sets of derating requirements are presented, one for coils and chokes designed to operate in the RF range, and the other for transformers and inductors operating at power rectification and audio frequencies.

This information is intended to be a general guide to aid the designer in the selection of an appropriate inductor or magnetic device for his intended application. More detailed information is available from vendors, MIL-STD-1286, MIL-T-27, and other publications. MIL-STD-1286 is particularly useful to military users because it details the various types of military-grade transformers, the advantages and disadvantages of each, and the behavior of each type under different operating conditions. A further source of information on the design of power supply-related magnetics is NAVMAT P-4855-1A, “Navy Power Supply Reliability Guidelines”. Complete listings of the military specifications are available from DSCC (Defense Supply Center Columbus) 3990 E. Broad St., Columbus, Ohio 43216-5000.

PACKAGING

Magnetic devices are available both in standardized and customized package styles. The standardized styles include chip, axial leaded, and radial leaded package styles. Chip style inductors typically range in value from 0.002 to 270 μH, and tolerances of ±5, 10, or 20%. Axial leaded coils typically carry higher inductance values (between 0.10 and 10000 μH), with package size greatly dependent on inductance value. Radial leaded packages are likewise available with a large variety of inductance values and sizes. Most variable inductors are manufactured in the radial leaded packages.

Magnetic devices can also be purchased in customized package styles. They are often designed for a specific application rather than manufactured in large quantities and purchased as off-the-shelf items. This is especially true for power transformers. Due to the high power density requirements in many power supplies, the designer cannot afford to waste real estate with unnecessary tapes or other features.

Unlike other passive devices, many types of magnetics (particularly transformers) are available at various levels of assembly. For example, many transformers can be purchased in potted packages with metal shields or as an individual transformer intended to be potted and shielded by the user.

The packages of magnetic devices are among the most massive of any component. This demands special mounting considerations to assure excessive forces are not exerted onto leads, especially in high shock and vibration environments, both in operation and while in storage. A general rule-of-thumb is to limit stress to 1/4 ounce per lead for small sized inductors, coils, and chokes. Stress must also be limited for large sized transformers, but these are usually designed to handle much higher stresses. Packages are also available with varying amounts of shielding. This is an important consideration where there is concern about the affects of electromagnetic fields.

FAILURE MECHANISMS & ANOMALIES

Relative failure modes of transformers and coils are shown in Table 1. Data shows they are equally likely to fail in either the open or short mode, but are about 3 times less likely to fail due to a shift in value. Most failures are related to heat. This document will restrict itself to a discussion of internal heating effects.

Table 1. Normalized Failure Mode Distributions for Transformers and Coils.1[1]

Failure Mode	Relative Probability
Open	42%
Short	42%
Parameter Change	16%

The most common cause of internal heat is from a lack of understanding of the frequency performance limitations of the device. The wire coil of a magnetic device is wound to give it the best performance over a specific frequency range. Operation outside this range results in overheating and eventual performance degradation. Operation at frequencies lower than the designed frequency range tends to saturate the core, while operation at higher frequencies increase core losses.

Heat can also be introduced from capacitive loads. Transformers that drive rectifier circuits with capacitive input filters require special consideration.

Capacitive loads cause the current through the transformer to be very non-linear (since the current used to keep the capacitor input filter charged is much greater than the average current delivered to the load). As a result, current is initially delivered as a series of spikes of much higher amplitude than the steady state current. Since transformer heating is a function of the square of the current, internal power dissipation increases more rapidly with a capacitive load over an inductive load.

Heating can also be caused by introducing DC current into a device that is not designed to handle DC. Small amounts of DC into an audio-type transformer, for instance, causes core saturation. This leads to a subsequent degradation in performance, particularly at low frequencies.

RELIABILITY

The failure rate of a magnetic device is most strongly affected by temperature. Specifically, it is dependent on how close the operating hot spot temperature is to the maximum rated temperature of its insulation material. For this reason, reliability prediction models base failure rate primarily on temperature and to a lesser extent insulating material. A comparison between the six most common insulating materials is shown in Figure 1. The failure rate models show there is relatively little change in reliability between most insulation materials, provided temperature is kept sufficiently below the maximum rated operating. The source of internal heat for a magnetic device is discussed under the section Failure Mechanisms & Anomalies. External heating sources can be caused from a large variety of sources and are considered outside the scope of this document.

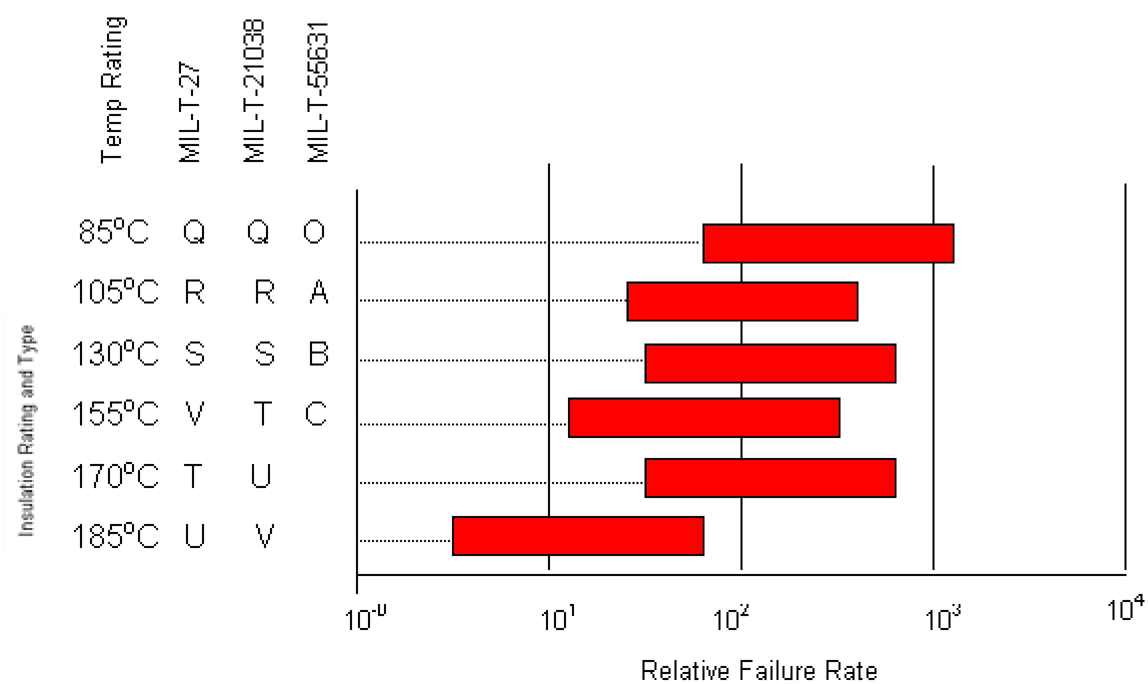

Figure 1. Relative Failure Rates for Magnetic Devices

A further reliability concern is inherent design and manufacturing deficiencies of customized magnetic devices. As a general rule, one-of-a-kind devices have higher failure rates than off-the-shelf items. This is because customized devices are typically manufactured in small lot sizes and there is less of an opportunity for reliability growth. Magnetics are therefore more likely than other passive elements to be tested and receive a power burn-in prior to assembly.

DERATING

Derating requirements are divided into two categories, dependent on frequency. Requirements for low frequency (audio), power, and pulse magnetic devices is shown in Table 2. High frequency RF coils are shown in Table 3.

Table 2. Derating Requirements for Transformers and Inductors (low frequency)

Parameter	Derating Requirement		
	Category 1 Protected	Category 2 Normal	Category 3 Severe
Hot Spot Temperature	30°C Below Specified Maximum	30°C Below Specified Maximum	30°C Below Specified Maximum
Current (Surge)	90% of Max	90% of Max	80% of Max
Voltage (Surge)	90% of Max	90% of Max	80% of Max
Additional Derating Requirements if Hot Spot Temperature is Not Known to High Level of Confidence:			
Current (Continuous)	70% of Max	70% of Max	60% of Max
Voltage (Continuous)	70% of Max	70% of Max	60% of Rated Max

Table 3. Derating Requirements for Coils and Chokes (High Frequency)

Parameter	Derating Requirement		
	Category 1 Protected	Category 2 Normal	Category 3 Severe
Current (DC)	90%	90%	80%
Hot Spot Temperature (Operating)	30°C Below Specified Maximum	30°C Below Specified Maximum	30°C Below Specified Maximum

Derating requirements for low frequency devices are further broken down into two categories, dependent on the level of confidence the user has in the hot spot temperature estimate of the device. The most important parameter to derate is hot spot temperature, but it is also the most difficult to determine. It usually needs to be estimated from a ΔT temperature rise from ambient based on power dissipation and radiating surface area of the device. Three methods of performing an empirical estimate of hot spot temperature are shown in Table 4. From top to bottom, they are listed in order of highest confidence to lowest (consequently, they are also listed in order of most to least difficult to compute).

High quality suppliers or suppliers conforming to established specifications will supply specification sheets with additional information to determine the ΔT temperature rise (e.g., a ΔT rise at full rated power).2[2]

Table 4. Estimating Methods for Determining Hot Spot Temperature	
Power Loss, Case Radiating Surface Area Method:	$\Delta T = 125\frac{W_L}{A}$ Where W_L: Power Loss (W) A: Radiating Surface Area (in^2)3[3]
Power Loss, Transformer Mass Method	$\Delta T = 11.5\,W_L/(M)^{0.5766}$ Where W_L: Power Loss (W) M: Transformer Weight (lbs.)
Input Power, Transformer Mass Method (Assumes 80% Efficiency):	$\Delta T = 2.1\,W_i/(M)^{0.6776}$ Where W_i: Input Power (W) M: Transformer Weight (lbs.)

Note: ΔT Represents the Temperature Rise from Ambient (T_A).

If there is a high degree of confidence in the hot spot temperature estimate for a magnetic device, it is acceptable to derate to hot spot temperature and surge current/voltage only, as shown in Table 2. If hot spot temperature is not known or the level of confidence is low, perform additional derating on continuous current and voltage, also shown in Table 2. This manual does not define an acceptable level of confidence because it is dependent on the particular application and device type. For example, there would be little concern about using the transformer mass method of Table 4 for a low power magnetic device intended for a room temperature application. In contrast, a transformer used in a three phase rectifying circuit for a shipboard application needs a much better estimate of hot spot temperature. It also depends on how close the temperature estimate is to the maximum permissible derated temperature.

Consideration should be given to imposing additional voltage derating on equipment intended to be used at low barometric pressure (high altitude or space) to protect against degraded dielectric properties and potential corona effects.

DESIGN & MATERIAL

If it is necessary to know the individual materials or design controls used in the manufacturing operation, consult the individual vendor.

FACILITY ASSESSMENT & QUALITY

Magnetic devices can be purchased with known quality and failure rate levels. These are determined by the vendor, based on testing. Magnetic devices conforming to the established reliability requirements of the Military specifications are identified by a failure rate letter designator, shown in Table 5. These carry a 60% consumer’s confidence level and are maintained at a 10% producer's risk. The confidence level of commercial magnetic devices may vary.

Table 5. Failure Rate Designator for Magnetic Devices Conforming to Military Specification Requirements

Failure Rate Letter Designator	Failure Rate (failures per 1000 hrs)
C	Non-ER
M	1.0
P	0.1
R	0.01
S	0.001

SAMPLING

For sample lot sizes used by the vendor, consult the individual specification requirements.

PROCESS CONTROL

Vendors manufacturing magnetic devices, conforming to the Military performance specifications, are required to implement an SPC system that meets the requirements of EIA-557. Typical processes applicable for SPC are coil windings, molding dimensions, final electrical test, final inspection, and production monitoring.

PART ASSESSMENT

Off-the-shelf magnetic devices are seldom subjected to additional testing or screening by the user. Customized magnetics and transformers used in high reliability applications are often tested, especially on a first piece basis. The most popular method of propagating early life failures and latent failure mechanisms without damaging inherent reliability is with temperature shock.

HANDLING & STORAGE PRECAUTIONS

No special handling precautions are necessary beyond what would be considered normal handling precautions to prevent damage during the assembly operation. Transformers and inductors are not considered ESD sensitive.

Closing Comments

Stress Screening: If there is a need for testing/screening to surface workmanship defects and infant mortality failures, thermal shock is recommended. Normal temperature cycling produces relatively benign benefits due to the high thermal mass of magnetic devices and subsequent slow temperature rate of change.

High Altitude/Space Applications: Recommend additional derating limitations be applied to voltage for applications that will experience low barometric pressure. Traditionally, derating guidelines for airborne applications (Air Force, NAVAIR, and NASA) recommend more restrictive voltage limitations, usually in the form of a 50% derating to both continuous and surge voltage. The rationale is to protect against the negative effects of low barometric pressures, such as lower dielectric voltages, increased corona effects, and the effects from condensation due to altitude/temperature changes.

Drawings: Assembly drawings for specialized magnetic devices are often complex and difficult to interpret. Companies do not use consistent formats, and some companies/suppliers use unique processes that are not reflected on assembly drawings. Therefore, first piece inspection and testing is recommended when switching vendors or when the build of a specialized magnetic device is sent to an outside source.

Mounting: Special considerations need to be given to the mounting of high power magnetic devices due to their relatively large mass in comparison to most other parts. Designers should attempt to mount massive magnetic devices on resilient mounting plates or to the edges of circuit boards. If solder connections are used to secure devices to a printed wiring board, limit stress to the solder connection to less than 8 grams (1/4 ounce) per lead.

Heat Sinks: Specifications for temperature rise from ambient (ΔT) of large power magnetic devices are often given under the assumption that the device will be mounted to a heat sink of a specific size. The size of the heat sink in some device specification is sometimes overly optimistic and may not be practical for many applications. Assure heat sinks have adequate capability to keep hot spot temperature below derating guidelines.

Adjacent Components: Power transformers can dissipate substantial amounts of heat. Attention must be paid to the mounting of adjacent components, especially capacitor filters and voltage regulators.

[1] Failure mode data for Table 2 was taken from a combination of MIL-HDBK-978, "NASA Parts Application Handbook," 1991; MIL-HDBK-338, "Electronic Reliability Design Handbook," 1994; "Reliability Toolkit: Commercial Practices Edition," Reliability Analysis Center (RAC), 1998; and "Failure Mode, Effects, and Criticality Analysis (FMECA)," RAC, 1993.

[2] Information on how magnetic devices are physically tested to determine temperature rise can be found in Para. 4.8.12 of MIL-T-27.

[3] Surface areas of MIL-T-27 standard case sizes can be found in Para. 11.3 of MIL-HDBK-217F, Notice 1 or can be computed from Figure 1 of MIL-T-27.