HIGH RELIABILITY MAGNETIC DEVICES

Design and Fabrication

COLONEL WM. T. MCLYMAN

Kg Magnetics, Inc.
Idyllwild, California

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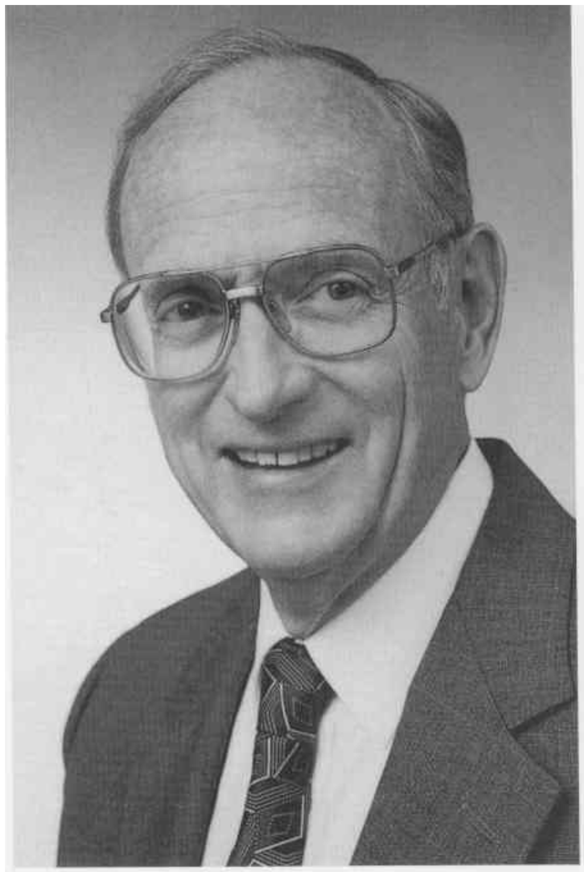

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Dedicated to C. Harris Adams

Graduated from California Institute of Technology

1949

Preface

This book is intended to provide guidelines and behind-the-scenes background to system and transformer engineers for the design and manufacturing of transformers and inductors of high reliability. There are many applications in which high reliability is a byword, such as manned space vehicles, spacecraft, satellites, flight control systems, missiles, and surveillance drones. Reliability is mandatory because of the high cost of component failure. Pursuing reliability in the manufacturing of transformers and inductors primarily involves attention to detail, coupled with close control in all phases of manufacturing.

I worked at the Jet Propulsion Laboratory (JPL) for almost 30 years as their magnetics design specialist. I have seen all types of vendors and magnetic components, some good and some bad. Frequently, components that were rejected were rejected because specifications were not followed. Shortcuts were taken thinking they would save time. Also, in many cases the design engineer would neglect to open the design manual that was provided. The engineer would design and fabricate the transformer or inductor the way he or she had done it on a previous job.

At JPL the guidelines used to design and fabricate high reliability magnetic components were previously found in the DM 509306, Volumes I, II, and III. These books are informative and I still have my original set. The required data is strung out in three volumes, making it very cumbersome to quickly locate anything in them, if one is not familiar with them. JPL finally updated them into a single volume, called JPL D-8208, which is still being revised.

With this book I have tried to bring together all of the existing pertinent literature into one volume. The information in this book comes from many sources: JPL DM 509306, Volumes I, II, and III, JPL D-8208, Mil-STD-981, Mil-T-27, NAVMAT P4855-1A, selected IEEE publications, and discussions with those with years of experience working with these components. Many of the lessons learned by these people have not been captured before in written form. It is hoped that this book will help in achieving standardization and aid in the reduction of the cost of high reliability and the need for custom magnetics. Hopefully it will also provide assistance in preventing design, manufacturing and/or testing mistakes.

The main goal of this book is to provide a comprehensive guide for every aspect of producing a high reliability magnetic component, from choosing the raw materials and construction techniques to in-process inspection, end item testing, and quality assurance recommendation.

Colonel Wm. T. McLyman

Acknowledgements

I worked at the Jet Propulsion Laboratory (JPL) for almost 30 years. I am proud to say that I worked on almost every major space endeavor that JPL was part of. I had many opportunities to work with Project Manager Tom Gavin, who would use my expertise as the magnetic specialist. It was here that I saw the need for a book that would explain the design and fabrication of high reliability magnetic components. In gathering the material for this book, I have been fortunate in having the assistance and cooperation of JPL, several other companies, and many colleagues. I wish to express my gratitude to all of them.

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Contents

A History of High Reliability Custom Magnetic Components, 1950 to the Present

In the years immediately following World War II, the military services recognized the need for and the wisdom of coordinating hardware specifications. During the War each service was procuring hardware using its own specifications. Many specifications were of very similar content. This plurality of similar, but not identical, specifications complicated all aspects of procurement including stocking and quality assurance. Joint Army-Navy specifications (JAN specs) were first written to coordinate separate specifications. Then came the Military specifications (MIL) intended for use by all services. This paper traces the history of MIL-T-27, a military specification covering custom magnetic devices.

Although MIL-T-27 was initially intended only as a specification for high-grade military magnetics, it has, over the years, come to be used as the document around which "high reliability" magnetic components are specified. Such procurements used MIL-T-27 in conjunction with other specifications, which imposed additional requirements.

Specification MIL-T-27 (no revision) was issued in September 1949. It was the first issue of an Army, Navy, Air Force joint document covering custom magnetic devices. MIL-T-27 had two parents. These were the Army document 71-4942 and the Navy document 16T30. These documents were those used prior to the issue of MIL-T-27 to specify custom magnetic devices.

Since 1949 MIL-T-27 has been subjected to several revisions leading up to the current Revision E. Table 1 lists the progressive revision sequence. Revisions over the years addressed, among other aspects, materials, construction, testing and quality assurance. Since the focus of this paper is directed primarily towards reliability, it is interesting to note that in the "A" revision (1955) the concept of life expectancy was added to the specification. Life expectancies of 10,000, 2500, and <500 hours were included. The thinking here was that in many applications, i.e., ordinance, the required life was seconds or minutes and that long term reliability was not needed.

Table 1

MIL-T-27 Rev.	Issue Date
Initial	September, 1949
Revision A	March, 1955
Revision B	September, 1963
Revision C	June, 1968
Revision D	April, 1974
Revision E	April, 1985

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It did not take long to recognize that, in most applications (high voltage perhaps excepted), it was not possible to design a magnetic component with a short life. Ultimate failure was brought about by external factors such as heat or physical destruction, not by a designed short life.

With the issuance of Revision D, in 1974, the "life" concept was abandoned and replaced by a design goal of 10,000 hours minimum life, a requirement buried deep within the revision (Par. 4.8.22). The fact of the matter is, though, that to have a high yield of parts lasting 10,000 hours, the average life must be many times greater than this.

There are several matters scheduled to be addressed in the future Revision F if and when funding becomes available.

It needs to be recognized that in dealing with MIL-T-27 that, by inference, also included are the other custom magnetic components which comprise the MIL-T-27 family: MIL-C-15305, MIL-T-21038, MIL-T-55631, and MIL-C-83446. The history of these other documents parallels the evolution of MIL-T-27.

Also, MIL-T-27 provides for "standard" parts. These parts are covered by individual specification sheets called "slash sheets." These parts differ from other MIL-T-27 custom parts only in that they are subject to listing on a Qualified Parts List (QPL). A slash sheet part is placed on the QPL whenever a supplier provides to the Government qualification for that part. The part may then be ordered from that supplier with minimum quality assurance for the three year valid period of the listing. QPL parts constitute a small percentage of magnetic devices built to MIL-T-27 and few new slash sheets are issued currently.

It goes without saying that two of the objectives of a military specification are to insure suitability and reliability. Magnetic components built to MIL-T-27 have always been quite reliable in the general sense. It was with the arrival of Sputnik and the following decades of space flight, including manned flight and including satellites needing long service life, that the term "high reliability" came to be applied to hardware destined for use in such applications.

The problem with which specifiers struggled over the years was how to define the word "high" in "high reliability." Magnetic devices built to MIL-T-27 from day one were pretty high in reliability. There are undoubtedly thousands upon thousands of devices built in the 50's and 60's, which are still functioning perfectly today.

The quest for "high reliability" was spearheaded by NASA since they were initially the users of devices for space applications. The growth of manned space flight has necessitated that NASA still be the leader in this effort. The military services and particularly the communications industry have welcomed and followed the NASA efforts. Reliability in all components is needed to protect the staggering investment required to build and orbit military and communication satellites.

Early efforts to specify "high reliability" magnetic components (what was really meant by higher reliability) came through user documents. These documents often detailed the construction of the component. Screening was added to eliminate so called "early failures". Thus reliability was enhanced by establishing tighter manufacturing controls and by conducting more rigorous inspection. This approach worked quite well as is evidenced by the success of most of the early satellites (electronically speaking).

There was another approach that was initiated in the 1960's. Since testing, no matter how rigorous, cannot absolutely guarantee how a component will fare over a long period of time, the concept of "established reliability" was suggested as a better way to "establish" reliability. The idea here was to demonstrate reliability statistically. Statistics can show the likelihood of failure of a large number of exact or very similar components.

This established reliability method has come to be the principal way reliability is established for components built in large quantities. These include resistors, capacitors and certain classes of inductors and EMI filters using inductors and capacitors. These components are used in such quantity that service life data can easily include the millions of hours needed to statistically demonstrate very high levels of reliability.

MIL-STD-975, first issued in 1976, is demonstrated statistically. Each component had its own previously developed and detailed specification, but MIL-STD-975 was the "overseer" document. MIL-STD-690 describes the statistical processes.

In the early days of the "established reliability" movement there was an attempt to bring "custom" magnetic devices into the fold. A document that was an established reliability version of MIL-T-27 was issued in 1964. It was called MIL-T-39013 and was born with great expectations.

MIL-T-39013 was hailed as the answer to specifying "high reliability" magnetics. Managers were delighted and issued requisitions to their purchasing departments for 10, 20, or even 100 pieces of devices built to

MIL-T-39013. Purchasing dutifully sent out requests for quotation (RFQ's). What happened, with hindsight, is easy to understand. With 2,000,000-plus hours of operation required to establish a space level reliability, most suppliers did not bid. Those who, tongue-in-cheek, went along entered a quote for 10, 20, or 100 parts with a quality assurance charge including 1000 parts in a 2000 hour life test regime, carefully burdened with an insurance policy. The outcome is easy to picture.

To the best of the author's knowledge, no procurement was ever placed to this document and it was retired ignominiously in 1971. It might be called a noble attempt but it should have been cleared upfront that the "established reliability" concept was not economically practical for any component built in small quantities and destined for a single application.

Following the demise of MIL-T-39013, the industry had no choice but to fall back on previously used methods of procuring higher reliability components:

1. Adding to MIL-T-27 additional quality enhancing requirements.
2. Generating a stand-alone, in-house document package.

In either case a complete document package would, or would not, include a detailed manufacturing requirement. Some users felt more comfortable if they controlled the design along with workmanship. Other users were happy with the supplier's design but controlled workmanship. Rigorous electrical, physical and environmental testing were a part of the specifications in either case.

Of significance, from an economic viewpoint, was the fact that with no standards there were major differences between the quality assurance provisions of users.

The cost of the preparation of these specifying documents and the cost of accommodating widely varying quality assurance programs dramatically increased the cost of the hardware.

In the early 1980's NASA recognized that there would be an increasing need for custom magnetic components and that costs for custom space level magnetic components must be controlled. What might do the job, it was envisioned, would be a new specification, that, when used with MIL-T-27, would provide the required reliability. Hopefully, this new specification would be adopted by all users. The continuing cost of writing new user specifications would be avoided. From this need was born MIL-STD-981.

The philosophy of MIL-STD-981 was based on what was, by then, obvious to users and suppliers: reliability of custom magnetic devices cannot be demonstrated statistically at any affordable cost. The alternative was that the required reliability must somehow be inherent in the design and manufacture. MIL-STD-981 was written with this intent. Its desired future was that it could eventually replace the increasing number of separate user specifications which had essentially the same objectives. The economies of this seemed quite clear.

MIL-STD-981, though, had a grander concept. It wanted to make its primary objective "build parts that will not fail in service" to an absolute (sic) fulfillment. A secondary objective, just as important from an administrative standpoint, was to engender a confidence among potential users that the primary objective could be realized. Otherwise, users would not adopt MIL-STD-981.

To accomplish its primary objective, MIL-STD-981 directs in minute detail standards for material, manufacture, workmanship, process control, and quality assurance. While MIL-T-27 remains the primary document for specifics of design and test, MIL-STD-981 imposes additional controls and workmanship standards. The documentation required by MIL-STD-981, in a sense, replaces the statistical records of established reliability parts, and provides objective evidence of reliability in its own way.

MIL-STD-981 has been revised twice, now at Revision B. Revisions have been the result of NASA-user-supplier conferences. At these conferences it was most gratifying to feel the camaraderie that existed among government and non-government participants. Clearly, each attendee had a sincere interest in helping the document to meet its objectives.

It is pleasing to note that MIL-STD-981 is rapidly gaining acceptance as the document of choice for space level magnetics. Magnetic components for the Space Station are being procured to MIL-STD-981. Other programs are espousing the document at an increasing pace. Many users are abandoning in-house documents and using MIL-STD-981. It clearly appears that MIL-STD-981 will be just as successful, and widely-used to specify high reliability custom magnetics, as are the established reliability documents now used to specify other passive components.

C. Harris Adams

Introduction

Transformers designed for operating in the environment of space must meet stringent requirements of high reliability, minimum size and weight, and high efficiency, due to unattended operation for a long period of time. Unlike terrestrial transformers, cooling of which is readily achieved by a combination of radiation and convection in the air at atmospheric pressure, the mode of cooling space transformers is conduction through the coil to the core and thence, by means of the mounting brackets, to a controlled heat sink. A relatively minor portion of the heat loss is transferred by radiation to surrounding objects or directly to space. Any voids or interference in the heat flow path, under vacuum conditions, will be disastrous to thermal resistance and will contribute to an excessive increase in temperature.

To achieve high reliability, it is mandatory to employ materials of construction that offer the maximum in thermal stability at the highest operating temperature, in order to ensure consistency of physical and electrical properties over the life of the system.

Certain combinations of flux density, frequency and magnetic material available to the designer can result in a smaller transformer, and therefore in lower copper losses and lighter weight.

Since heat conduction through the core is a major mode of heat transfer in space transformers, the thermal conductivity of the core material is a major factor in rising temperatures of the transformer.

Most space transformers are required to operate in air at atmospheric pressure for a period of time for preflight test purposes and hence the design criteria are those for a transformer operating in air and moisture.

Operating in air is accomplished by impregnation and encapsulation of the coil, and in most instances, the entire transformer is encapsulated. The insulating material and resins used should possess negligible outgassing characteristics.

Desirable properties of the resin are low viscosity, low shrinkage on cure, low coefficient of expansion, low temperature cure and good thermal conduction characteristics. Processing includes baking out the coil to remove moisture, treating under vacuum for several hours to remove occluded gasses, introduction of the resin under a vacuum, and then soaking the coil in heated resin for a time sufficient enough to allow the liquid to impregnate the coil.

While careful selection of materials and the use of the appropriate manufacturing processes and procedures are key contributors to long life and reliable performance, it is also important that the design, fabrication and application of transformers for space be supported by an effective product assurance program. Reliability, availability, maintainability, configuration control and environmental testing and qualification requirements must be defined early in the design and development process. The manufacturing cycle should be controlled and monitored by a conscientious quality assurance program, which includes appropriate in-process inspection points, and testing activities to prevent workmanship defects and assure delivery of a highly reliable end product.

James C. Arnett
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Symbols

α	regulation, %
A_c	effective cross section of the core, cm^2
A_p	area product, cm^4
A_t	surface area of the transformer, cm^2
A_w	wire area, cm^2
$A_{w(B)}$	bare wire area, cm^2
$A_{w(I)}$	insulated wire area, cm^2
A_{wp}	primary wire area, cm^2
A_{ws}	secondary wire area, cm^2
AWG	American Wire Gage
B_{ac}	alternating current flux density, tesla
ΔB	change in flux, tesla
B_{dc}	direct current flux density, tesla
B_m	flux density, tesla
B_{max}	maximum flux density, tesla
B_r	residual flux density, tesla
B_s	saturation flux density, tesla
D_{AWG}	wire diameter, cm
E	voltage
Energy	energy, watt-second
η	efficiency
f	frequency, Hz
F	fringing flux factor
F.L.	full load
G	winding length, cm
ε	skin depth, cm
H	magnetizing force, oersteds
I	current, amps
I_c	charge current, amps

ΔI	delta current, amps
I_{in}	input current, amps
I_m	magnetizing current, amps
I_o	load current, amps
I_p	primary current, amps
I_s	secondary current, amps
J	current density, amps per cm^2
K_e	electrical coefficient
K_f	waveform coefficient
K_g	core geometry coefficient
K_u	window utilization factor
L	inductance, henry
λ	density, grams per cm^3
l_g	gap, cm
l_m	magnetic path, cm
MLT	mean length turn, cm
MPL	magnetic path length, cm
μ_i	initial permeability
μ_Δ	incremental permeability
μ_m	core material permeability
μ_r	relative permeability
μ_e	effective permeability
n	turns ratio
N	turns
N.L.	no load
N_p	primary turns
N_s	secondary turns
P	watts
P_{cu}	copper loss, watts
P_{fe}	core loss, watts

P_g	gap loss, watts
P_{in}	input power, watts
P_o	output power, watts
P_p	primary copper loss, watts
P_s	secondary copper loss, watts
P_Σ	total loss (core and copper), watts
P_t	total apparent power, watts
R	resistance, ohms
R_{ac}	ac resistance, ohms
R_{cu}	copper resistance, ohms
R_{dc}	dc resistance, ohms
R_o	load resistance, ohms
R_p	primary resistance, ohms
R_s	secondary resistance, ohms
R_t	total resistance, ohms
ρ	resistivity, ohm-cm
S_1	conductor area/wire area
S_2	wound area/usable window
S_3	usable window area/window area
S_4	usable window area/usable window area + insulation area
T	total period, seconds
T_r	temperature rise, degrees C
VA	volt-amps
V_c	control voltage, volts
V_d	diode voltage drop, volts
V_{in}	input voltage, volts
V_o	output voltage, volts
V_p	primary voltage, volts
V_s	secondary voltage, volts

ΔV_p	delta primary voltage, volts
ΔV_s	delta secondary voltage, volts
W	watts
W_a	window area, cm^2
w-s	watt-seconds
W_{tcu}	copper weight, grams
W_{tfe}	iron weight, grams

HIGH RELIABILITY MAGNETIC DEVICES