The Electromagnetic Compatibility (EMC) Design Challenge for Scientific Spacecraft Powered by a Stirling Power Converter

Noel B. Sargent
Analex Corporation, Brook Park, Ohio

National Aeronautics and
Space Administration

Glenn Research Center

October 2001

Available from

THE ELECTROMAGNETIC COMPATIBILITY (EMC) DESIGN CHALLENGE FOR SCIENTIFIC SPACECRAFT POWERED BY A STIRLING POWER CONVERTOR

Noel B. Sargent
Analex Corporation
Brook Park, Ohio 44142

ABSTRACT

A 55 We free-piston Stirling Technology Demonstration Convertor (TDC) has been tested as part of an evaluation to determine its feasibility as a means for significantly reducing the amount of radioactive material required compared to Radioisotope Thermoelectric Generators (RTGs) to support long-term space science missions. Measurements were made to quantify the low frequency magnetic and electric fields radiated from the Stirling's 80 Hertz (Hz) linear alternator and control electronics in order to determine the magnitude of reduction that will be required to protect sensitive field sensors aboard some science missions. One identified "Solar Probe" mission requires a 100 dB reduction in the low frequency magnetic field over typical military standard design limits, to protect its plasma wave sensor. This paper discusses the electromagnetic interference (EMI) control options relative to the physical design impacts for this power system, composed of 3 basic electrical elements. They are: (1) the Stirling Power Convertor with its linear alternator, (2) the power switching and control electronics to convert the 90 V, 80 Hz alternator output to DC for the use of the spacecraft, and (3) the interconnecting wiring including any instrumentation to monitor and control items 1 and 2.

INTRODUCTION

An optimal solution to achieving EMC for the Stirling Radioisotope Power System (SRPS), (DC out for power distribution to the satellite), and protection of the electric and magnetic field instruments aboard the spacecraft requires the trade-off of many variables. This initial assessment is an attempt to quantify the magnitude of the EMI control issues, and to explain in broad terms the relationships that are at work in the determination of the design options. *Good EMI engineering enables the design process, and should not constrain it.*

The SRPS is assumed to be composed of 3 basic electrical elements: (1) the Stirling Power Convertor (SPC) with its heat source and linear alternator (LA) as shown in Fig. 1, (2) the power switching electronics (PSE) and associated control electronics to convert the nominal 90 V, 80 Hz SPC output to DC for the use of the spacecraft, and (3) the interconnecting wiring including any instrumentation to monitor or control items 1 and 2. More subtly involved are stray capacitance and inductive effects between these components and structure that cause currents to flow in paths that are not on the electrical schematic! There is significant stray capacitance between the stator coils and structure whether we like it or not. These leakage paths are also very significant for the power conversion and control electronics since they operate at higher frequencies. Furthermore these stray current paths take different routes (the one of least impedance) as a function of frequency.

THE METHODOLOGY OF EMI CONTROL

The first instinct is to solve all electromagnetic radiated field problems by shielding. Actually this is the last line of defense to be applied after proper electrical grounding (controlling current flow in structure and circuit loop area) and filtering (frequency-band limiting of unintentional currents). Indeed shielding will be required, particularly to control low frequency magnetic fields to protect the very sensitive science instruments. It is the overriding goal of this paper to sort out all the effects important to specifically
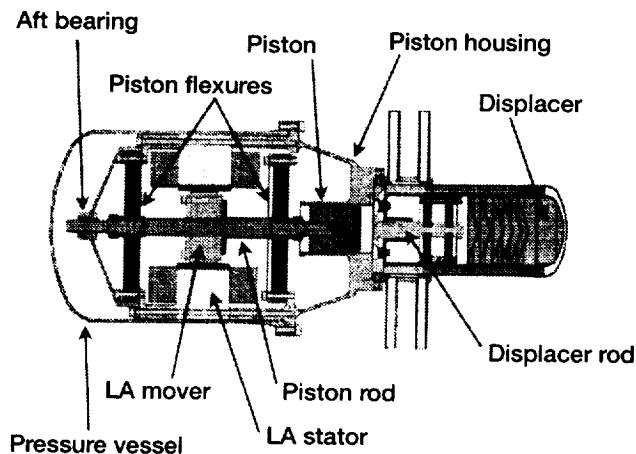
Figure 1.—Stirling power convertor.

solving the design issues of Stirling, so that informed decisions on weight, thermal and structural requirements can be made while providing minimally intrusive EMI design and shielding solutions. Project managers must provide for an EMI control plan that defines the EMI control methods in the very earliest stages of design if optimal solutions are to be applied. Design retrofits are rarely sufficient, or efficient!

THE LINEAR ALTERNATOR

The first area to attack (but perhaps not the most difficult) is that of the electrical machine, to ensure that its design results in the lowest residual magnetic field possible. It is not the purpose of this report to mandate specific design fixes but rather to suggest a list of options that will result in controlling the magnetic path to the maximum extent possible. These may include a copper band called a "shading ring" intimately contacting and completely covering the perimeter of the core laminations and stator coils at the outside boundary of the machine to control the eddy currents at the surface and hence the leakage flux. The shading ring, also known as the "shorted turn method," is a technique used on open-core transformers that may have merit for the proposed LA design. Then choose a material for the pressure vessel, or combination of materials, that gives improved magnetic shielding performance over 304 stainless steel alone (no real weight penalty here). Shielding materials will need to be an integral part of the electromechanical design for the entire SRPS. The mechanical aspects of the shielding design are equally as important as choosing the proper material. Close attention is required to holes, seams, sharp transitions, and wire penetrations that can destroy most of the shielding effectiveness of the chosen material. Additionally, care should be taken to minimize the total loop area of the interwinding connection path prior to exiting the machine. The fact that the flight SPC will be a

hermetically sealed unit is a big plus, however care must be taken to control all penetrations so as not to destroy its inherent shielding effectiveness.

THE SPC CONTROLLER

An electronic controller is necessary to regulate the LA output power of the SPC in a way that limits the travel distance of the LA mover. The method of control used on the TDC was a zener diode that clipped the LA voltage and hence disturbed the current waveform. This produces harmonic distortion that shows up both in the output current waveform, and in the radiated magnetic field, beyond the 40th harmonic, decreasing at the rate of 40 dB per decade of frequency, as shown in Figs. 2 and 3 respectively. The flight controller design should be one in which the electrical current output is sinusoidal so that the harmonic content is dramatically reduced. Such a digital controller design has been demonstrated at GRC with a reduction in harmonic content of 30 dB for the 2nd and 3rd harmonics and at least 60 dB beyond the 8th harmonic. Should the magnetic field shielding design prove too heavy to achieve the "solar probe" mission magnetic field requirement of -30 dBpT/$\sqrt{Hz}$ at 1 meter, it is far more acceptable to relax the limit at a single frequency that can be accounted for as a single line in the scientific data spectra, than throughout the entire 150 kHz passband of interest.

EFFECTS OF INTERCONNECTING WIRING

Maxwell's equations have been reduced to the absolute simplest algebraic form possible to more easily emphasize important concepts related to design trade-off. In most cases the equations are presented in logarithmic form (the EMC engineer's favorite) so that they directly fit the "limits" of the EMI requirements.

Assume that 1 A of sinusoidal current is flowing at the power frequency. For current flowing in a long single wire, the magnetic field at distance "r" (1 meter in this case) can be simply expressed as dBpT = dBµA – 14. One amp (120 dBµA) produces a 106 dBpT magnetic field, or a whopping 136 dB over the science requirement of -30 dBpT/$\sqrt{Hz}$ at 1 meter distance. Notice that the field intensity is linear with distance. The SPC does not have one wire, but a closely spaced pair with equal (almost) and opposite current flow. However, any common-mode current circulating between the SPC and the PSE through structure will have this "single wire" characteristic. So it only takes 0.16 µA of common mode current to exceed the requirement [-30 dBpT = 20 log(0.16) – 14]. This could be a tough design challenge and so a high permeability solid tube between the SPC and the case of the PSE may be warranted as a conduit for all wiring. If the dimension of the radiating source is comparable in
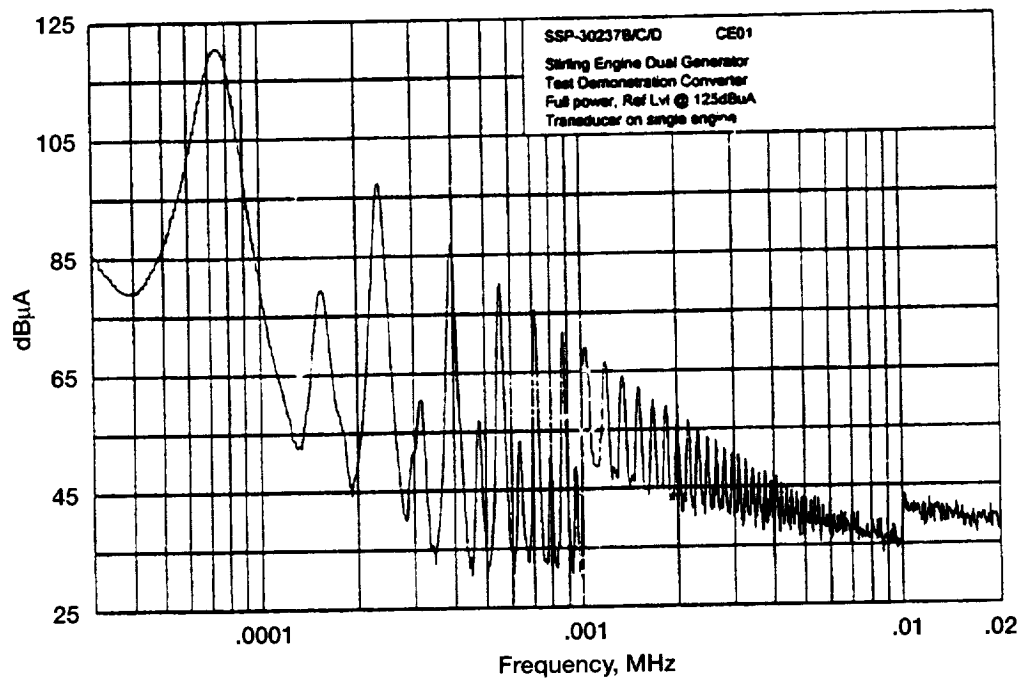
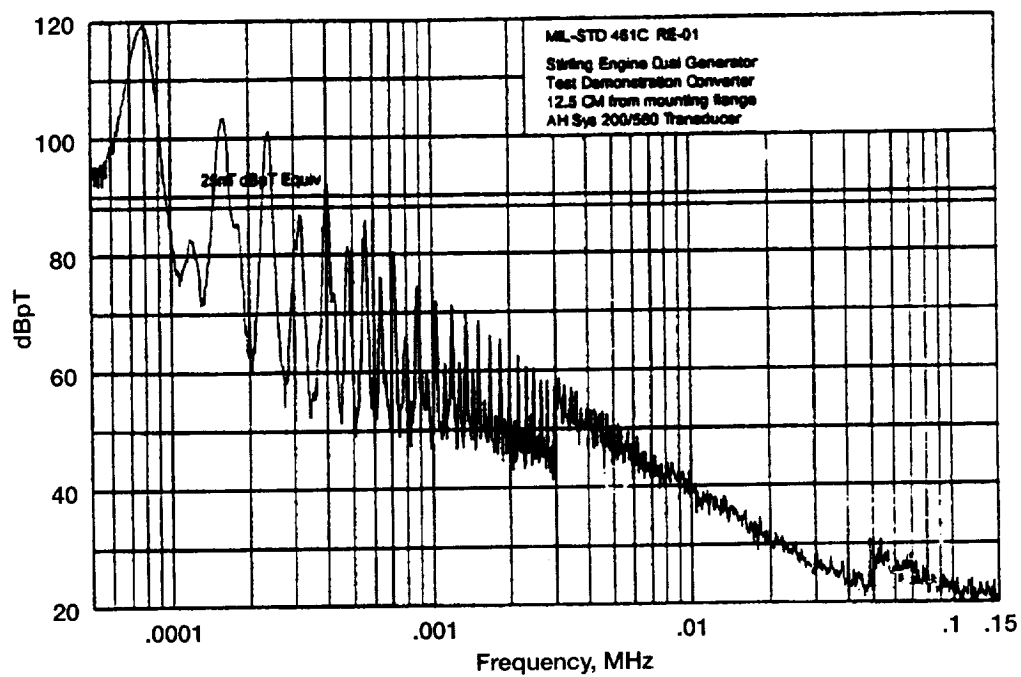Figure 2.—CE01, 30 Hz-20 kHz, powerline conducted emissions.

Figure 3.—Radiated magnetic field emissions, 30 Hz-15 kHz at 12.5 cm from convertors.

size to the distance at which the field is measured, a current loop may also be an appropriate model.

For two closely spaced wires carrying the same but opposite current, the magnetic field at 1 meter is dBpT = dBμA −14 − 20log($\frac{s}{r^2}$), where "s" is the spacing between the wires. Note the field from closely spaced wires varies as $\frac{1}{r^2}$. Assuming the 1 A wires are spaced 5 mm apart, dBpT = 120 dBμA − 14 − 20 log(0.005), or 60 dBpT, still a huge 90 dB over the limit. Twisting of the two wires gives roughly another 12 dB reduction dependent on load impedance and circuit balance. There are other wiring configurations using twisted quads and flat-plate lines that are worth investigating if the interconnecting lines are very long, however another 20 dB or so is all the help one should count on. So there is great advantage of co-locating the PSE at the SPC if at all possible or as mentioned, containing the wiring in a solid tube if co-location is not feasible.

For compact magnetic sources with a closed, tightly coupled magnetic path, like transformers, motors, and the SPC, the magnetic field falls as roughly $\frac{1}{r^3}$ as long as the source is small compared to the measurement distance "r." Models have been developed to calculate this residual flux from the linear alternator by Geng et al. Measurements with the LA alone in the near future would aid this modeling effort.

THE PHYSICS OF SHIELDING MATERIALS

Shielding materials will certainly need to be an integral part of the electromechanical design of the SRPS. The mechanical aspects of the shielding design are equally as important as choosing the correct shielding material. It is worth restating that lack of attention to seams, holes, sharp radius transitions, and wire penetrations can destroy most of the shielding effectiveness of the chosen shielding materials.

The total shielding effectiveness (SE) of a material is the sum of 3 factors: the absorption loss (A), the reflection loss (R), and a multiple reflection loss (B) for thin shields. The multiple reflection loss is of little practical importance if the absorption loss is greater than 10 dB as will be the case in the SRPS design, so that SE = A + R, in dB. As an impinging electromagnetic wave (Ei) encounters a conductive or ferromagnetic material, its amplitude decays exponentially by producing current flow in the material and hence ohmic losses and heating of the material. The resultant exiting wave out of the shield (caused by the current that is actually able to flow completely through the material), (E_s) obeys the equation $E_s = E_i * e^{-\frac{t}{\delta}}$, where t (in meters) is the material thickness, and δ (in meters) is the "skin depth"

or the distance required for an attenuation of 1/e or 37 percent of the impinging value of the field. These expressions can be further simplified to give an absorption loss term A = 8.7(t/δ) dB, so that the absorption loss through any material is simply 8.7 dB per "skin depth." Engineering charts are available listing skin depths of various materials. However, skin depths are a nonlinear function of frequency for each material. This means the best shielding material (for absorption loss) at low frequency is not the best material for higher frequencies. From a practical point of view that crossover point between high conductivity materials (copper) and high permeability materials (mu-metal) is between 100 kHz and 1 MHz. This means that the shielding material design for the LA magnetic field emissions will be different from that of the power conversion electronics.

The reflection loss term is not as simple to visualize since the loss depends on the impedance of the wave and the media at the shield interface (usually air). The largest reflection (best attenuation) occurs at the first boundary (entering) of the material for electric (high impedance) fields, but at the secondary boundary (exiting) for magnetic (low impedance) fields. In the case of electric field shielding, very thin sheets (foils) provide good SE, however the SE of very thin sheets is much less for magnetic fields. Because of the effect of wave impedance, it is always advantageous to locate the shield as close to the source of electromagnetic energy as possible (in the near field). So, the reflective loss (best in high conductivity materials) varies with frequency, distance from the source, and wave impedance. Wave impedance (high or low compared to free space of 377 Ω) is best intuitively understood if one remembers this relationship: circuits containing high fluctuating currents (dI/dt) produce magnetic fields which are low impedance, and circuits containing high dV/dt compared to the current (dV/dI > 377 Ω), produce electric fields which are high impedance.

In order to take advantage of the best material properties for optimizing both absorption and reflection, copper and magnetic alloy materials may be combined into a sandwich. This combination not only provides maximum reflection at low frequencies where energy absorption is low for both low impedance and high impedance waves, but also increases absorption at high frequencies.

To summarize total shielding effectiveness, the bottom line is shielding low frequency magnetic fields (<100 kHz) requires a thicker high permeability material (mu-metal), and shielding electric fields at all frequencies requires only thin but high conductivity materials (copper). Remember the shield must be a sardine can—no seams or penetrations—for maximum performance. This is the challenge for real world mechanical design. In practice, the actual total SE is limited by the number of thin slots, penetrations, and the shape of the enclosure. Various means can be used to overcome the shield penetrations, like creating "thick holes" by using extension tubes at apertures. Wiring penetrations (and

to some extent mechanical fasteners) are by far the most difficult to control since the wires also efficiently conduct coupled energy through the shield, free to re-radiate on the other side. Filtering is the only hope here, and low frequencies are very difficult to filter.

POWER CONDITIONING ELECTRONICS

It is necessary to convert the nominal 90 V, 80 Hz output of the linear alternator to DC voltages useful to the spacecraft. This conversion is accomplished by the PSE. Since the EMI science requirements are most stringent below 150 kHz, the power switching frequency should be at a frequency above 150 kHz, well within today's state-of-the-art. This also puts the unintentional emissions of the switching electronics at a frequency that is much more efficient to filter in terms of filter component size and weight when compared to lower switching frequencies. It is always more effective to provide filtering for wires exiting an electronic circuit, than it is to control the resultant radiation by shielding. The PSE should be in a completely shielded module (sardine can) with filtered input and output wiring. Additional metal partitioning within the box is an effective means to control coupling from the power electronics to the control or instrumentation functions. The PSE should be located as close as possible and preferably integral to, the SPC to reduce the interconnecting lead lengths toward zero.

THE INSTRUMENTATION ISSUE

In the near term development configuration, it will be very difficult to directly verify the "solar probe" magnetic field science requirement of -30 dBpT/$\sqrt{\text{Hz}}$ at 1 meter. Typical EMI loop antennas and flux gate magnetometers are orders of magnitude too insensitive to provide this measurement. Most coil-type magnetic field antennas are simply several turns of wire in an electrostatic shield (so that the electric field is not measured; only the magnetic field). Simply stated, the voltage developed at the terminals of the loop antenna is equal to the number of turns, times the loop area, times the frequency, times the field being measured ($V = 2\pi n A f B$). The typical sensitivity of a top of the line oscilloscope or spectrum analyzer is 0.1 µV, so that at low frequency it is difficult to use an antenna of this type. Also the facility required to reduce the ambient background noise at 60 Hz, to a level that will not saturate the measurement system, may be expensive and bothersome to maintain.

Alternate methods may be used for verification of this requirement that in the end will be more accurate and repeatable. This involves an additive sequence of measurements that will allow direct calculation of the base requirement. Once the radiating sources and rate of decay of their fields have been established, measurements may be made at closer distances. The shielding effectiveness of the pressure vessel itself can be measured, as well as shielded versus unshielded test configurations. Wiring currents can be measured and resultant fields calculated using expressions similar to those developed in this paper, once the circuit and field generating geometries are known. It may well be that the linear alternator is the easiest element of the SRPS to control because of its hermetically sealed configuration, dependant on the selection of materials allowed for the pressure vessel.

Care should be taken in the construction of any test engine fixtures where magnetic field measurements are important, to limit the amount of extraneous magnetic material. This extra material may alter the radiated magnetic flux path in a way that is detrimental to obtaining accurate, representative test data.

The complement of instrumentation should contain a flux gate magnetometer for the DC and low frequency (<100 Hz) magnetic field, and an induction coil sensor for the AC magnetic field. Sources for each type are being explored with candidate types identified that will meet the requirements. In addition it is almost a necessity to have a low frequency (10 Hz to 200 kHz) spectrum analyzer (not just an oscilloscope) capable of resolution bandwidths of 1 Hz or below (as a means of controlling the noise floor of the measurement).

CLOSING REMARK

It is hoped that this simplified view of the EMI design challenge will provide an insight into the physics of these interactions. This paper is primarily intended to sensitize the multidiscipline design team that only through frequent interaction, can the level of EMI control required by the SRPS be maintained throughout the design, and particularly the fabrication process. For this reason, EMI design engineering decisions must be considered beginning with the conceptual design phase of the program.

REFERENCES

Steven M. Geng, Gene E. Schwarze, "A 3-D Magnetic Analysis of a Linear Alternator for a Stirling Power System," NASA/TM—2000-210249, 2000.

Richard Furlong, Richard Shaltens, "Technology Assessment of DOE's 55-We Stirling Technology Demonstrator Convertor (TDC)," NASA/TM—2000-210509, 2000.

Clayton R. Paul, "Introduction to Electromagnetic Compatibility," 1992.

Henry W. Ott, "Noise Reduction Techniques in Electronic Systems," Second Edition, 1988.

Donald R.J. White, "Electromagnetic Interference and Compatibility," Vol. 3–EMI Control Methods and Techniques, 1978.

REPORT DOCUMENTATION PAGE

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	October 2001	Final Contractor Report

4. TITLE AND SUBTITLE

The Electromagnetic Compatibility (EMC) Design Challenge for Scientific Spacecraft Powered by a Stirling Power Converter

6. AUTHOR(S)

Noel B. Sargent

5. FUNDING NUMBERS

WU–896–30–00–00
NAS3–00145

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Analex Corporation
3001 Aerospace Parkway
Brook Park, Ohio 44142

8. PERFORMING ORGANIZATION REPORT NUMBER

E–12799

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA CR—2001-210945
IECEC2001–CT–37

11. SUPPLEMENTARY NOTES

Prepared for the 36th Intersociety Energy Conversion Engineering Conference cosponsored by ASME, IEEE, AIChE, ANS, SAE, and AIAA, Savannah, Georgia, July 29–August 2, 2001. Project Manager, Jeffrey Schreiber, Power and On-Board Propulsion Technology Division, NASA Glenn Research Center, organization code 5490, 216–433–6144.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Categories: 20, 26, and 33   Distribution: Nonstandard

Available electronically at http://gltrs.grc.nasa.gov/GLTRS

This publication is available from the NASA Center for AeroSpace Information, 301–621–0390.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

A 55 We free-piston Stirling Technology Demonstration Convertor (TDC) has been tested as part of an evaluation to determine its feasibility as a means for significantly reducing the amount of radioactive material required compared to Radioisotope Thermoelectric Generators (RTGs) to support long-term space science missions. Measurements were made to quantify the low frequency magnetic and electric fields radiated from the Stirling's 80 Hertz (Hz) linear alternator and control electronics in order to determine the magnitude of reduction that will be required to protect sensitive field sensors aboard some science missions. One identified "Solar Probe" mission requires a 100 dB reduction in the low frequency magnetic field over typical military standard design limits, to protect its plasma wave sensor. This paper discusses the electromagnetic interference (EMI) control options relative to the physical design impacts for this power system, composed of 3 basic electrical elements. They are (1) the Stirling Power Convertor with its linear alternator, (2) the power switching and control electronics to convert the 90 V, 80 Hz alternator output to DC for the use of the spacecraft, and (3) the interconnecting wiring including any instrumentation to monitor and control items 1 and 2.

14. SUBJECT TERMS

Mars; Stirling engines; Deep space; Nuclear electric power generation; Roving vehicles; Electromagnetic interference; linear alternator

15. NUMBER OF PAGES

11

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	