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AEROSPACE INFORMATION REPORT

AIR 1394

Issued February 1978
Revised

CABLING GUIDELINES FOR ELECTROMAGNETIC COMPATIBILITY

1. INTRODUCTION

1.1 Foreword: These cable practice recommendations tend toward design guidance rather than standardization. EMC achievement tests can be standardized, but the means for achievement should not be constrained. The material can best be described as an essay on cabling, and the theme is that a cable is just a part of a complete circuit, the interconnect circuit. Cable EMC performance is thus determined largely by circuit design; it is unrealistic to expect cabling techniques to compensate for improper impedance, symmetry or waveform in the circuit.

1.2 Background: Cables are system elements containing interconnect circuits, and these cause more interference than do circuits contained inside boxes. Circuits in general exhibit a class of EMI problems related to conduction which includes crosswalk, ground loops, common impedance coupling and sneak circuits. All result from a unique characteristic of electric conduction; the current delivering energy from source to load must flow in a closed path, a circuit. As illustration, consider the functional flow diagram for any system and compare with the wiring schematic; function lines usually will not be found to correspond to wires in any consistent, simple manner. Perhaps 20% of the functional flow lines do correspond one for one with nominally "complete" transmission lines; e.g., pairs or triples, coaxes or triaxes. The rest of the function lines are implemented with single wires sharing a common return or, frequently, finding a return elsewhere. Even the nominally "complete" transmission lines are seldom truly complete; typical lines lose several percent of the fundamental return and most of the harmonic return in other cables and in structure. The functional flow lines which represent one-way energy flow are, in other words, implemented with circuit flow, that is, loop flow. This results in large apertures and shared impedances, both of which cause interference. Conduction and induction interference is more of a chronic problem in cable circuits than in single chassis circuits, or even in long distance transmission circuits. Chassis circuits and long distance lines are unified designs, the latter having matched drivers and receivers. Cable circuits in contrast are not really designed. Typically, the driving and receiving end circuits are given to the cable designer as constraints, and he then must make the best of them. For these two reasons; i.e., circuitous flow and fragmented design, cables require careful attention early in any program. This AIR, therefore, stresses integrated design of the entire interconnect circuit.

1.3 Definition of Interconnect Circuit: The term "interconnect" refers to wiring which connects circuitry inside one box to circuitry inside another box some distance away. Noting that there are "boxes" within, and upon, other "boxes" in complicated units, the essential feature of an interconnect is that it traverses system structure. A "box circuit" in contrast stays within, or on the (metal) surface of one unified chassis.

An interconnect circuit consists of cable wires plus their terminating circuitry in the boxes at each end and at any intermediate junction box. These latter driving and receiving elements will be called end-circuits; they are, nevertheless, incomplete circuits, being part of the complete interconnect circuit.

Circuitry which is complete within one chassis may be called box circuitry. Multi-rack circuits like computer circuits are "box circuits" if the racks are bonded into a continuous bay, but should be thought of as "interconnect circuits" if the racks are electrically distinct from each other. Figure 1 illustrates these definitions.

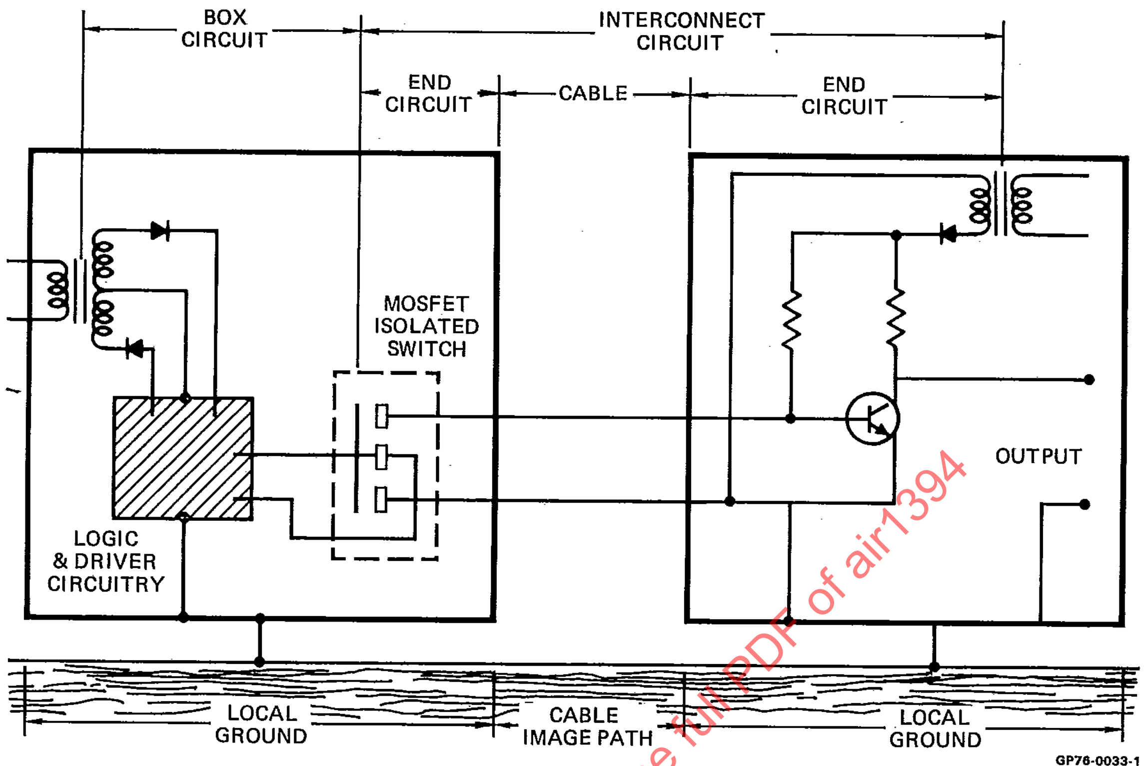


FIGURE 1
INTERCONNECT CIRCUIT

1.4 Coupling and Containment: The first and most obvious prerequisite for interference is transfer of energy, that is, coupling. At great distance, coupling consists of emission, path and reception. At close range; e.g., between two circuits in a cable, coupling consists of induction and conduction. Coupling is controlled by the "geometric" measures, twisting, balancing, and shielding in contrast to the "modulation" measures of para. 1.5. Coupling results from poor containment of energy within physical envelope and so the term "containment" can be used to describe both the goals of bottling up and excluding energy. The second section of the guide, "Interconnect Circuit Design" deals entirely with prevention of coupling between a circuit of interest and some environment.

The degree of containment that should be designed into a circuit for compatible operation in the system (e.g., whether or not to twist, shield or balance) depends upon many factors. The least understood, yet most important factor, is the one generally called "influence factor", and this is taken up next.

1.5 Influence Factor: In order for one interconnect circuit to interfere with another, the coupled signal of para. 1.4 must be of certain frequency, have certain modulation, and occur at certain times, and these specifics depend on the frequency, modulation and timing of the receptor. The need for twisting, shielding, balancing and so forth, therefore depends on this mutual "time-frequency" relationship, as well as on the "space-amplitude" relationship; i.e., energy transfer. The modifying effect of time-frequency coincidence upon the situation has been called "Influence Factor.":[1]

Effective interference signal = (Coupled signal) x (Influence Factor)

1. From telephone practice; e.g., Telephone Influence Factor for Power lines near telephone lines.

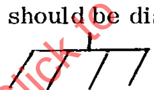
In the example of the reference, the influence factor for powerlines vs telephone lines describes the harmonic power falling within the speech bandwidth. Influence Factor is decreased by time and frequency control measures, such as gating, coding, frequency translation and rise time control. The modifying effect of Influence Factor upon containment design is difficult to forsee. Nevertheless, the protection afforded by time-frequency measures must be considered in order to avoid shielding overdesign.

An extremely large interfering signal can cause a category of response different from that just discussed. Demodulation, overloading or damage can occur when the signal exceeds normal limits. The Influence Factor concept does not apply to such conditions.

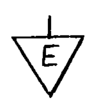
1.6 Ground: In electrical usage "ground" means a current sink of infinite capacity. An ideal ground must, therefore, be large enough to return a sink current to its source wherever that might be. An ideal ground must also be highly conductive and accessible. Not all regions have a ground; if a continuous conductor extends and is accessible throughout a region then that conductor forms "ground" for that region. This intuitive concept of ground is analagous to the frame of a mechanical system.

If a system cable pattern is made up of many small loops (dense population of boxes highly interconnected) and if a ground is desired, then it should be a plane. If two such regions situated some distance apart are joined into one system by long cables, then a criterion for the ground link is needed. To require that both ends of the link be at the same potential could be unrealistic. The general criterion is that the ground link be wide enough and close enough (to the link cables) to enable formation of a good image of the link cables. This requires that the ground link carry the full net distributed charge on the link cables. This is the criterion for an elongated ground.

Usage has blurred the meaning of the term "ground". In common usage "ground" can mean either a true ground as described here, or just a wire that eventually connects to power common. It is recommended that the term "ground" be specifically modified if other than true ground is meant. To this end, the classic upside down "tree" symbol should be discarded; it no longer has meaning. The chassis connection symbol



is definitive and useful: Whether or not chassis is a good ground, there is no doubt about the meaning of this symbol. In most aircraft and spacecraft the structure is the only true ground available, so the chassis connection symbol becomes synonomous with a ground connection. All other connections to ground-like conductors should be identified with modified symbols, for example

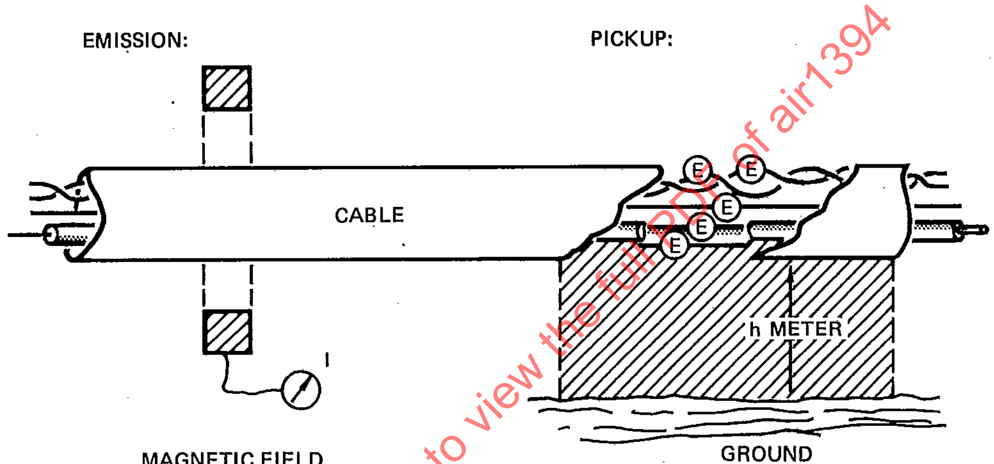


for which a complete description is provided.

1.7 Models For Environmental Coupling: When two circuits are being designed to work together with no third party, then the problem variables are mutual ones: mutual inductance, mutual capacitance, relative power and relative timing. In the more usual case, an individual interconnect circuit is designed, tested, and qualified for an anticipated environment and specified level of emission. Constraints for this problem are based on some kind of assessment of Influence Factors (See 1.5) between the circuit and the eventual system. The problem variables in this artificial half-situation are environmental ones. Recommended models for use in the important low frequency range up to 1 MH_Z are described below.

Emission from the circuit to the environment is best measured in terms of net monopole source current and charge. The net current in the interconnect wire bundle can be defined to be the reading of a clamp-on ammeter. This variable corresponds to the dominant mutual inductance of the complete two-circuit situation. The net charge per unit length of the bundle is not readily measured because a suitable probe is not readily available. The rod antenna of MIL-STD-461 provides an indirect measurement. Net charge is, nevertheless, the variable which determines the radial (monopole) electric field of the bundle. Net charge corresponds to the dominant mutual capacitance in the complete two-circuit situation. Dipole and higher order source variables exist and can be significant. However, it is seldom necessary to consider multipole sources during circuit design; twisting and light shielding will always control the higher order fields, should control be needed.

The effect of environmental magnetic field on the circuit under design can be represented by voltage generators of equal value put in series with each wire of the circuit bundle. The common value of voltage equals the derivative of the expected magnetic flux threading the loop between bundle and ground, plus any IR drop in ground. This value for the equivalent generator can be called the "reference shift" to which the circuit is subjected. This reference shift corresponds to the effect of mutual inductance and resistance in the complete two-circuit situation. The effect of environmental electric field on the circuit can be represented by current generators in shunt with each wire. Diagrams of the four models just described appear in Figs. 2a and 2b.



MAGNETIC FIELD,

$$H = \frac{I}{2\pi r} \quad \frac{\text{AMPS}}{\text{METER}}$$

(NEGLECTS MULTIPOLE FIELDS OF WIRE CURRENTS AND THE FIELD OF THE RETURN-CURRENT)

$I \equiv$ MAGNITUDE OF CABLE NET CURRENT IN TIME DOMAIN

FLUX INDUCED EMF PER UNIT CABLE LENGTH,

$$E = \mu h \frac{dH}{dt} \quad \frac{\text{VOLTS}}{\text{METER}}$$

(NEGLECTS DIFFERENTIAL PICKUP AND DISTRIBUTION OF H OVER A; NEGLECTS SHIELDING DUE TO EDDY CURRENT IN SHIELD-GROUND LOOP)

H = MAGNITUDE OF MAGNETIC FIELD IN TIME DOMAIN

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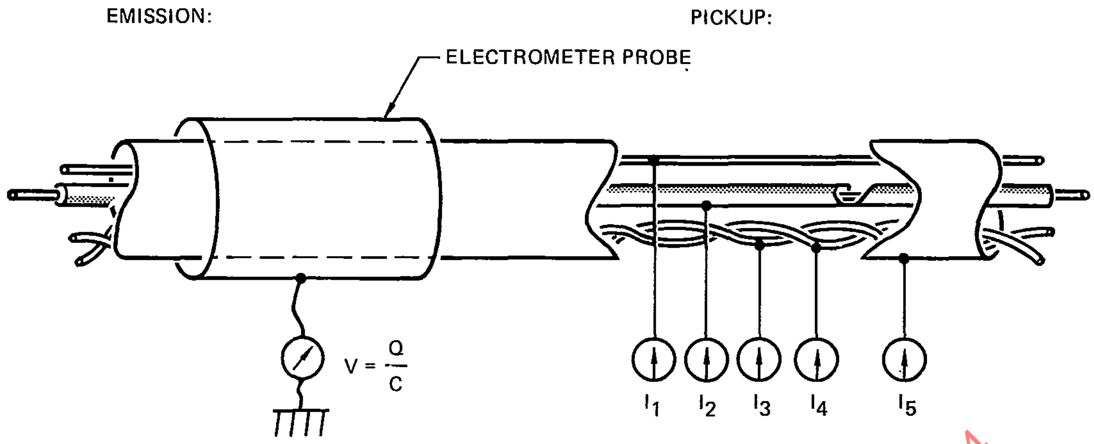
FIGURE 2a
ENVIRONMENTAL COUPLING MODELS - MAGNETIC



ELECTRIC FLUX,

$$D = \frac{Q}{2\pi r} \quad \frac{\text{COULOMBS}}{\text{METER}^2}$$

(NEGLECTS MULTIPOLE FIELDS OF DIFFERENTIAL VOLTAGES, AND NEARNESS OF OTHER CONDUCTORS)

C = NET CAPACITY PER METER OF CABLE

V = COMMON MODE VOLTAGE

Q = COULOMBS OF NET CHARGE PER METER OF CABLE

SHUNT CURRENT PER UNIT CABLE LENGTH,

$$I_n = W_n \times \frac{dD}{dt} \quad \frac{\text{AMPS}}{\text{METER}}$$

(NEGLECTS DISTORTION OF CHARGE ON SOURCE CABLE DUE TO RECEPTOR CABLE NEARNESS)

W_n = EFFECTIVE WIDTH OF CONDUCTOR n: APPROXIMATELY THE REAL WIDTH REDUCED IN PROPORTION TO SHIELD COVERAGE

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FIGURE 2b
ENVIRONMENTAL COUPLING MODELS - ELECTRIC

2. INTERCONNECT CIRCUIT DESIGN

2.1 Preliminary Design: Electrical energy can be transferred by means of conduction, induction or radiation. Of these, conduction is the most versatile; together with induction and relay coupling, electrical conduction accounts for almost all cable transfer in use today. Conduction is not necessarily the choice of the future. Hybrid techniques for interchange of information and small amounts of energy over moderate distances are being developed. Light coupling links from gap-size to tens of meters in length are in use. Experimental work continues in electro-chemical techniques similar to neuron transmission and synaptic coupling. Hybrid techniques will become increasingly useful in spacecraft and non-metal aircraft. Conduction is yet the most feasible mechanism and because of this the preliminary designer must make an early assessment of structural conductivity and circuit isolation.

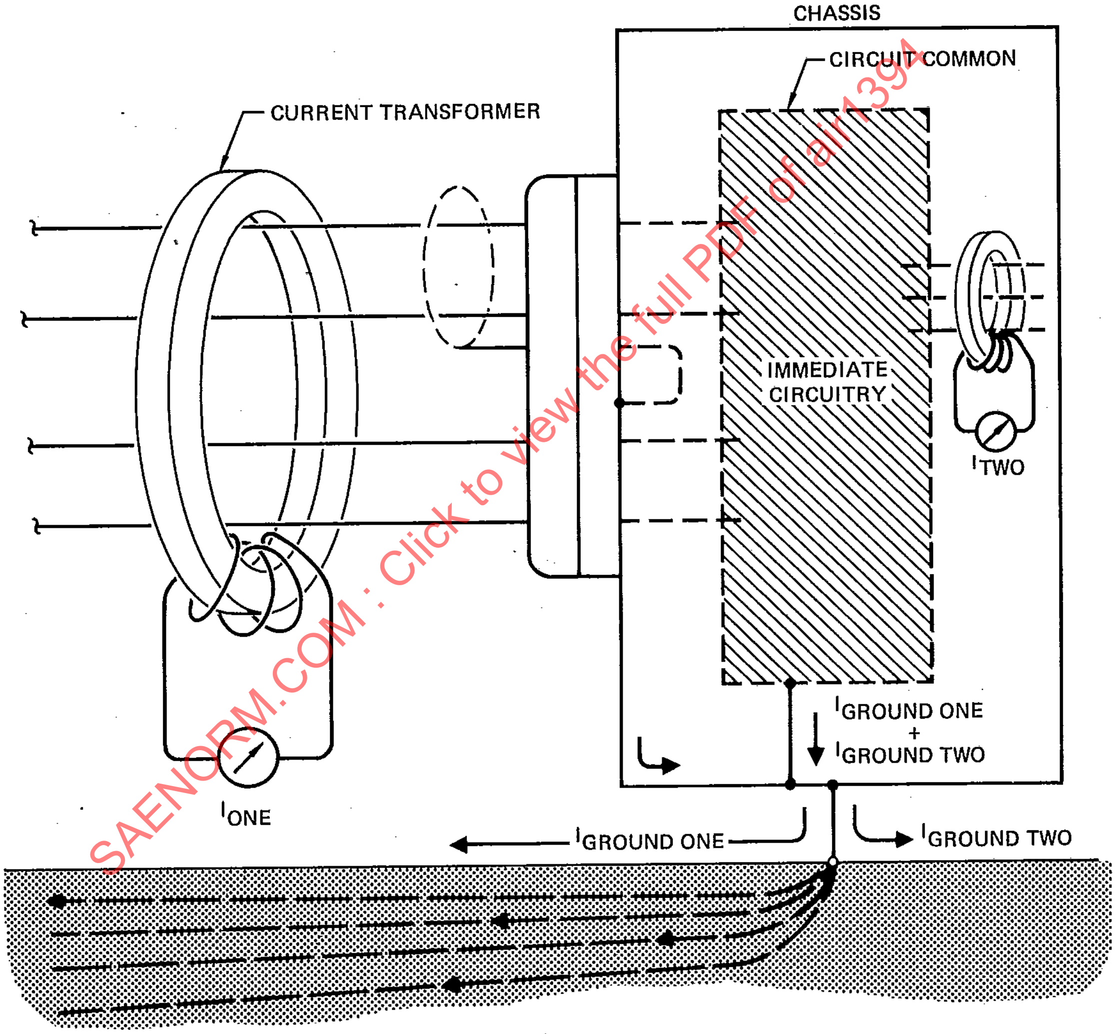
The cost of achieving EMC in cabling is roughly the sum of circuit cost and ground plane cost. In some aircraft under development wiring is put into conduit because the structure does not provide a good enough ground plane; this cost can be traded with the cost of optical or other high performance isolation.

The quantity of isolators needed in a system given no ground plane depends in large measure on the number of loops in the functional flow map. A radial pattern has no loops and can in principle be put together without isolators by floating the circuits in the radial terminator boxes. In contrast, a function loop automatically requires at least one isolator.

2.2 Return Current Rule: Regardless of how moderate may be the goal for containment according to system analysis (See 1.4 and 1.5), there is a minimum quality EMI design criterion which should always be met. This is the one-to-one rule implied earlier. Interconnect circuit current paths should correspond one-for-one with functional flow paths. The rule in effect requires that return flow must either be bundled with forward flow or be imaged in adjacent ground; return flow can never be allowed to seep back through a route-of-opportunity in another cable. Consider the interconnect circuit wiring in Fig. 3. This set of conductors includes all wires and wire shields labeled with a common function. The net current in this set due to nominal generators (exclude environmental current) should by the one-to-one rule,

a. be zero, or else

b. return completely in adjacent ground.



RETURN CURRENT RULE REQUIRES THAT:

$$I_{ONE} = \begin{cases} \text{ZERO OR,} \\ I_{GROUND\ ONE} \end{cases}$$

CONVERSELY, NO PART OF I_1 MAY APPEAR IN I_2.

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FIGURE 3
RETURN CURRENT RULE

The next two topics are guides to designing circuits to meet this minimum criterion. There are two basic kinds of circuit which can be made to correspond one-to-one with functional flow; balanced, and unbalanced with ground return. Almost all practical aerospace circuits that meet the one-to-one rule exhibit varying degrees and kinds of balance, depending on frequency. The practical design of any circuit, therefore, derives from both balanced and unbalanced design principles.

2.3 Balanced Interconnect Circuits: The EMI parameters of balanced circuit design are:

Value - distribution and voltage threshold of common mode impedance

Kind - distribution and degree of balance.

Common mode impedance is a property of the loop formed by the circuit, taken as one conductor, and system ground plane. This impedance opposes environment-driven current, and for best results should be obtained by isolation at both ends of a circuit. Isolators are subjected to the full common mode stress of the environment and must, therefore, be rated accordingly.

Balance strictly means impedance balance, but some kind of EMI performance is gained by voltage or current balance alone. Balance is a characteristic not only of the two end-circuits but also of the cable. The ideal design will balance all three elements. The degree of balance is directly related to performance, which is to say containment.

The ultimate balanced design is perfectly symmetrical throughout and has infinite common mode impedance at both ends (and the cable theoretically has infinite common mode inductance). This ultimate circuit can be grounded in any manner to any ground without degradation. Practical designs need to approach this ideal to a degree depending on containment goal and available quality of ground.

The degree of containment achieved by an actual balanced design depends on the variables listed above. The benefit of common mode impedance is measured by the ratio of this impedance to the impedance of the ground path traversed. Circuit common mode impedance should ideally be distributed between driver, cable, and receiver in proportion to the distribution of ground impedance along the circuit path. This is a generalization of the practice of isolating circuitry at breaks in structure.

2.4 Unbalanced Interconnect Circuits with Ground Return: The class of circuit discussed here is single-ended and double grounded. For the mixed case in which one end is totally isolated, the foregoing comments about balanced design are also pertinent.

2.4.1 Principle of Operation: The ground plane return circuit[2] achieves EMI performance by forming an image in nearby ground of the net interconnect flow. The field of the interconnect circuit is thereby minimized because the opposite current and opposite net charge density are close instead of far away. The fact that both ends are referenced directly to system common potential makes this circuit sometimes usable for logic and switching systems.

2.4.2 Dependence Upon Ground: The dominant variable in unbalanced interconnect design is the extent and conductivity of avaliable ground. (Titanium, for example, is such a poor conductor that the ground image is far outside the skin). The ground path width must be larger than the cable height by a ratio depending on the upper frequency limit desired for effective containment. The path from end-circuit through ground to other end-circuit must be bonded.

2.4.3 Impedance: Normal mode impedance is more of an EMI issue in unbalanced design than in balanced design due in part to the larger circuit area. Moderate values around the norm of 377 Ω (ohms) are best. Too much impedance can be compensated for by shielding, but the too little impedance cannot be compensated for except by drastic ground plane features. For this latter reason, power cannot be returned in ground without certain precautions.

[2] The phrase "ground plane return" is used to describe any circuit connected at both ends to a good ground image path; the term thus includes RF coaxial circuits even though their return current may be kept inside the cable by skin effect at some frequencies.

2.4.4 Frequency Limit: Ground plane return of non-coaxial flow is feasible up to distances of perhaps one-tenth wavelength. At frequencies above this implied limit, the return for interconnect flow must be brought into the cable. This is accomplished by the use of radio frequency packaging methods.

2.4.5 Redundant Return Wires: A so-called "return" wire which proves to be grounded at both ends will not carry very much of the normal mode current. Such wires, therefore, are beneficial, but not very much so. Coax outer conductor is an exception.

2.5 Isolation: In electrical usage, "isolation" means the isolation of current in one circuit from current in another. The usual connotation is that energy is supposed to transfer from one to the other without intermingling of current. Isolation, therefore, marks the true beginning and end of a circuit. A system like a computer having no internal isolation becomes one single circuit for EMI purposes.

Isolation impedance is specified in ohms of capacitive and resistive common mode impedance; usual practice is to specify resistance and shunt capacitance. Common mode impedance is that measured between the reference of primary and the reference of secondary. Isolation impedance can be a misleading parameter if not accompanied by a circuit diagram. The criterion for acceptability of a given isolation is that it be large compared to the normal mode impedance of either circuit. In the case of three-terminal devices like the junction field effect transistor, the "isolation" impedance can be very high without accomplishment of any isolation of current whatsoever. Serious interface problems are continually being caused by the popular notion that "isolation" impedance is a sufficient description of isolation performance. This is true only if the impedance is truly a common mode impedance, and this can exist only for devices of at least four terminals. Depending upon the objective, it is possible to substitute balance for impedance: a differential receiver providing only 25 Ω of common mode impedance can yet achieve near-perfect isolation of current solely by virtue of balance. While this solution fails in severe magnetic field environments, it illustrates the limitation of the concept of isolation impedance. Another technique which can isolate current without high common mode impedance is the "emitter ground". If the emitter of a coupling transistor is connected directly to true ground, then the base current will not flow in the collector circuit. Specifications should include a circuit diagram, a normal mode/common mode ratio, or other clarification in addition to isolation impedance.

Any isolation device has a limited range of linearity to voltage stress. The limit ranges from 5 V for some solid state devices to millions of volts for long optical links. Specifications of common mode isolation should, therefore, include the maximum anticipated voltage stress.

2.6 Structural Conductivity: The degree and extent of conductivity provided by structure strongly influences interconnect circuit design. The reason for the interrelationship is that structure alone is sufficiently massive to approximate a ground plane. The trend in structures is toward less conductivity due to non-metals, moving joints, thermal isolators, and titanium. Before selecting interconnect design concepts, the necessary image paths in structure should be traced and evaluated. Shortcomings in degree, width or continuity indicate some special action is needed; one can either upgrade the circuitry to zero current bundles or else attempt to create adequate image conduction.

The complete set of image paths needed is not always found by first inspection. Most large systems are made largely of purchased boxes. Every electrical tie to chassis within a box, whether it be a shield pigtail, a capacitor, or a circuit wire, is a potential source of structure current. Few system makers take the trouble to dig out internal wiring details and integrate these into a system wiring diagram. It, therefore, should be assumed that every cable requires an image path; it, therefore, should also be assumed that poor structure conductivity will impact circuit performance.

2.7 Interconnect Wire Type: The primary EMC criterion for wire choice is that the wire impedance symmetry to ground should match the symmetry of driver and receiver impedances to ground. Where these two differ in symmetry, the end which is grounded should dominate. For example, a balanced isolated switch joined by two cable conductors to a grounded single-ended receiver is a circuit of hybrid symmetry; the single-ended symmetry dominates, and the correct wire is coax.

Balanced interconnect circuits are cabled with symmetrical wire; e.g., pairs. The normal mode loop area should be minimized. Twisting tighter than that required to hold the wires together is usually unnecessary.

Shields add capacitance which in some circuits causes phase shift and rise time problems. If a circuit's impedance and threshold dictate shielding, but the shielding causes phasing problems, then the circuit cannot be cabled, and redesign is indicated.

Whereas the circuit designer should specify the type of cable wire, it is also true that other factors often constrain the interconnect circuit to the use of available wire types. This is a recurring problem in space vehicle umbilicals, multi-contractor interfaces and "buried" cables, as in an airplane wing. Mutual inductance and capacity data for such "standard" cables is not in the present data inventory, and this means that the circuit designer must over design for EMC.

2.8 Circuit Shielding: Circuit shields may be divided roughly into two kinds; environmental shields and "circuit completion" shields. The former serves purely to isolate circuit from environment, whereas the latter both does this and also has a circuit function. As noted in para. 2.7, preceding a shield may inadvertently become part of its circuit.

2.8.1 Circuit Shield Types: A partial listing of shield types will illustrate the foregoing comment:

a. Noise Shield - A purely environmental shield added or not, based on system compatibility considerations.

b. Low Level Instrumentation Shield - An environmental shield that also has a strong circuit completion function. Also called "driven shield".

c. Triax Outer Conductor - Although put there for noise, it will also carry some signal if the cable is used for digital data.

d. Twinax Outer Conductor - Much like the foregoing, this conductor nominally carries no signal current, but its role in fixing line impedance clearly places it in the circuit completion class.

e. Digital Bundle Shield - As data rates approach the HF region, parallel data wire bundles will become multimode transmission lines in which the return flows both in a wire and upon the inside of the shield.

2.8.2 Requirement for Noise Shield: The question of whether or not to place an individual shield on a circuit derives from a study of voltage, impedance and Influence Factors for the circuit in relation to probable cable-mates and in relation also, to the more distant environment. The result may indicate a need to shield against the far environment only, in which case a bundle overall shield is adequate. Finding the answer to the question solely by analysis is for practical purposes impossible. This AIR just recommends that experience be modified by some kind of analysis involving Influence Factors. To shield "just in case" is not good practice.

If it does become necessary to shield, then certain modifying information should accompany the requirement:

i) Upper Frequency - State the highest significant frequency

ii) Shielding Mode - State whether the shield protects (or contains) primarily the differential mode or the common mode

iii) Material - Shield construction details are significant, and in critical cases should be included.

2.8.3 Termination:

a. Radio frequency shields require strong terminations regardless of supposed mode of primary function. However, at lower frequencies a shield which protects a balanced circuit does not necessarily need to be grounded at all.

b. Except for driven shields, a shield should connect only to true ground, never to a wire or to a bus.

c. A shield on a double grounded circuit should be double grounded. A shield on a single point grounded circuit should be grounded only at or near that single point.

d. Termination via pin or via connector shell is a matter to be resolved quite early. Pin grounding can be made effective up to about 10 MHz, with effort. (Overall shields should never be brought into a box on a pin.) Pin grounding requires roughly one pin per circuit in high performance situations.

2.9 Connector Assignment: The criterion for assignment of box internal wires to a connector should be completeness of circuit. Where a number of wires share one or more returns, then all the highs and all the lows should route through a single connector. The term "circuit" may not include enough, however. Suppose that two complete circuits interconnect a pair of boxes and that for some reason a connection exists between the circuits at each end. (The connection might be a small capacitor.) The idea of completeness then requires that both circuits be routed through a single connector, otherwise the net current in each of separate connectors would not be zero. If we distinguish in this way between minimum functional completeness and inadvertent enlargement of a circuit, then an enlarged term is needed. The term "family" connotes individual completeness, enclosed by a higher level of completeness, and this is the term suggested for use in connector assignment criteria (See Fig. 4). The criterion for assignment of box internal wires to box connectors is completeness of "family". Each family of wires, wire shields, and wire shield pigtails should be put through a single connector. If the family is incomplete because of return via true ground or structure, then that is acceptable (See Return Current Rule, para. 2.2).

The criterion for including more than one family in a connector is that the two or so families should be compatible if tied together the full distance. Stated differently, the two or so families could be put inside one overall shield for the full distance and be compatible.

The above criteria are ideal. They lead to simple, straight forward routing. The departure of splitting a family is acceptable if the family has no overall shield and the two connectors are close together. The departure of putting incompatibles in one connector is acceptable if the dissident parties are headed for different terminals (and if the few inches together can be tolerated).

3. CABLE DESIGN

3.1 Scope and Objective: Cables are a prime path for interference because of their relatively large coupling aperture compared to boxes. Nevertheless, very little EMI control can be accomplished by cable measures in comparison with box measures. The cause of this paradox is that the primary source of cable coupling, that is monopole field, cannot be controlled very well by cable techniques. The magnetic monopole field for a bundle can be reduced only by moving the bundle closer to the return monopole cable or to structure, whichever applies; this is usually impractical. The electric monopole field of a bundle can be reduced by a well terminated shield; however, cable breaks at bulkheads, and so forth, lead to pin-sharing and loss of containment. Overall shields do not have this problem, but they become unmanageable in a highly branched cable system. Cabling should not be permitted to cause problems, but cabling should not be expected to correct box problems.

The main EMC objective in cabling should be to complement the design of the end-circuits. This leads to the requirements of family completion and wire symmetry, and these are primary. Secondary cabling EMC controls measures are grouping, add-on shielding, and routing. Knowledge of the complete interconnect circuit being cabled is essential to achievement of good compromise design. This knowledge may be transmitted in the form of "interconnect schematics".

3.2 General Recommendation: The process of organizing many individual circuits into installed wire harnesses should begin by choosing which wires must be close together, proceed to choosing which wires can be close together, and conclude by choosing which wires must be separated. Because the first step unifies each circuit (to minimize self inductance), it follows that the next step, combining for convenience, deals not with individual wires but with complete circuit sets. In like manner, the final step juggles rather large groups. This three level process forms the outline for this section.

Technical decisions at the mid and final levels of combination address the question: can two given circuits or groups of circuits be routed closely together? Two approaches are in common use. These are called routing-by-function and routing-by-signal.

Routing-by-function is the name given here to the philosophy of confining each subsystem to a small volume so that space between subsystems can be cleared. Because "subsystem" is not a precise term, this routing approach amounts to the following descending order of priorities:

1. Combine the wires from one connector.

2. Combine the wires from one box.

3. Combine the wires from boxes supplied together as a subsystem (one maker or one designer).

Part of the idea in routing-by-function is to delegate subsystem self-compatibility problems to the subsystem designer; this frees the system EMC staff to work inter-subsystem problems.

Routing by signal is the name given here to separating wiring of disparate energy level. There are a number of cable coupling models around which compute coupled signal-to-noise ratio as a function of waveform, impedance, geometry, and relative energy. The models range from oversimplified "nomograph" types to complete equivalent circuits with analytical solutions. Part of the idea of routing-by-signal is that candidate routings should be computed; one sign of a routing-by-signal job is precision in the statement of separation distances. In some instances, wiring is categorized to indicate its potential for causing interference ("high energy") and its potential for being compromised by interference ("sensitive"). Categorization by energy seeks to ease the computation workload and to prevent EMI problems during field retrofit. This procedure is risky due to the element called Influence Factor (para. 1.5). Categorization schemes cannot take this into account and, therefore, lead to oversimplification. Categorization is not recommended. The recommended retrofit approach is that the kit designer decide the routing and provide explicit instructions in terms of functional wire identification.

Routing-by-signal makes sense within a subsystem, and routing-by-function makes sense at the system level. Highly integrated spacecraft tend to be routed by energy level, whereas airplanes tend to be routed by function.

3.3 <u>Circuit and Family Design:</u>

3.3.1 <u>Completion</u>: The first priority in cable design is to locate all conductors belonging to each circuit and see to it that these conductors do not become separated. This reduces the emitting and receiving aperture. Poor connector assignments can make successful completion difficult by making it necessary to route one wire of a pair close to a box when the wire should have been inside the box. Identification of all conductors of a circuit is not always a simple matter of observation. At the bleakest, box schematics are seldom visible enough to the cable designer to permit independent determination. At best, the circuit of interest is connected to other circuits, such that analysis alone can point out the true extent. Fig. 4 illustrates an enlargement of the boundaries of a circuit to include closely related circuitry. Such an enlarged "circuit" can be called a "family". The family is the largest wire set normally included within one private shield. The distinction is that a circuit contains just enough wires to do its job, whereas a family has extra wiring that is connected to the circuit for packaging, common power, or other reasons. Summarizing, the design purpose is to identify families and keep them together.

3.3.2 <u>Wire Type</u>: Cable wire type should either reflect the recommendation of the interconnect circuit designer or be chosen as described in para. 2.7. The result may conflict with mechanical and economical needs. A circuit family, for example, might ideally be carried in two twisted pairs inside a common shield; this makes a poor cable. Because of situations like this, the cable designer often needs to re-evaluate circuit design. In developing compromise cables, it is best to give up twisting before giving up proper symmetry (See para. 2.7). This rule reflects the fact that twisting only affects normal mode, differential, containment; whereas inconsistent symmetry generates monopole fields. Driver and receiver end-circuit equivalents or schematics need to be available in order to determine optimum compromises.

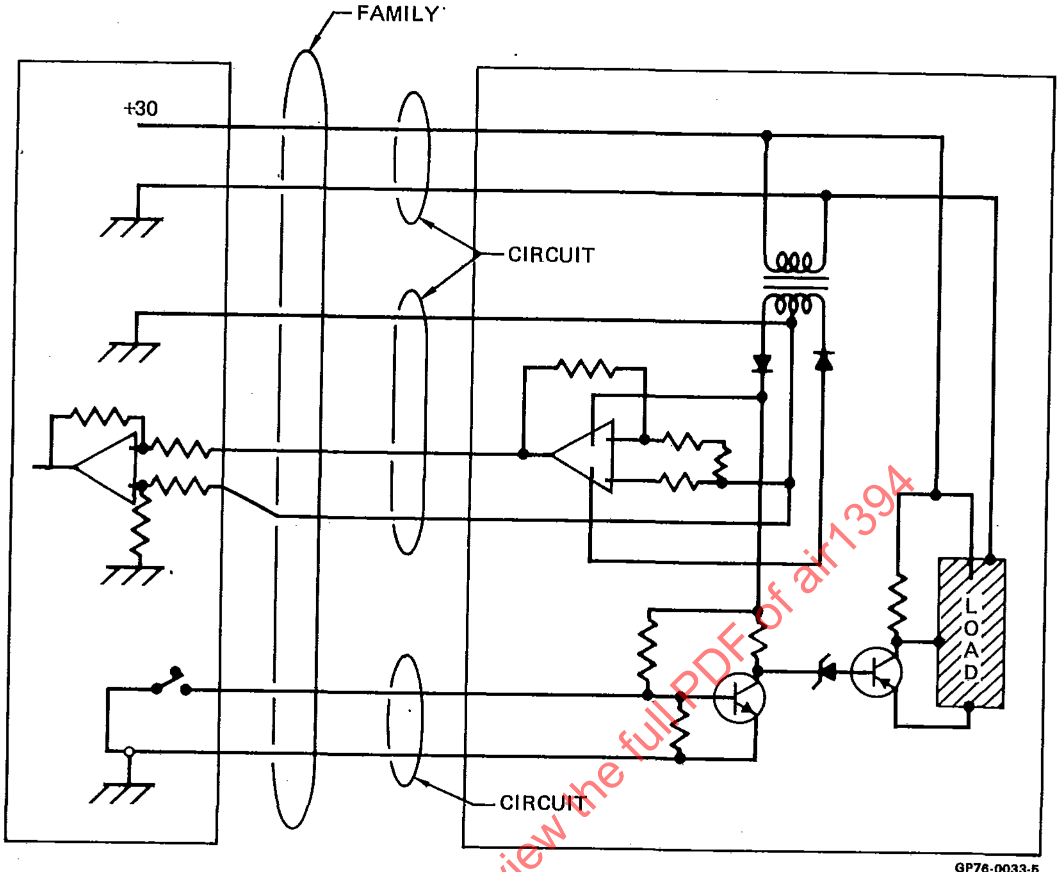

FIGURE 4
CIRCUIT AND FAMILY

3.3.3 Private Shield: Private shields (See para. 2.8) exist to control circuit capacity and to decouple. It is, therefore, necessary in general to avoid contact between private shields except at, or very close to ground. It follows that shields which are run through a bulkhead connector on a common pin should be reviewed to see whether the several contained circuits might not be able to share a common shield. Private shields operating above about 10 MHz must be terminated to the connector shell rather than to a pin.

3.4 Group Design:

3.4.1 Combination: As introduced here, a "group" is the largest homogeneous and compatible wire set in which a circuit or family can be placed. This criterion makes the "group" correspond to the largest wire set normally included within one overall shield; however, shielding is not implied. The group idea is the kernel of the recommended approach to routing. Instead of first deciding on separations, the recommendation is to first decide on combinations. The result is groups. (Groups take the place of "EMI categories".) Grouping can be based on homogeniety of signal or of function (See para. 3.2). Because of the homogeneous requirement, a group will inherit a natural name and this is preferred to naming on the basis of a deduced property. It is recommended that group names also identify sub-system. A group may be contiguous or spread out: switched lighting wiring, for example, might be a group and this would not be one connected bundle.

The dilemma illustrated in Fig. 5 is chronic in integrated design systems. The using box combines power and data in one connector. Does the power belong in a power group or in a user group? How about the date? Unless the supplier requests otherwise, the best rule is to favor the using box and include both power and data in a use-named group (e.g., "camera"). In fact, this recommendation holds even though the two originate in separate connectors. This reasoning, as stated in para. 3.2, prefers to separate subsystems from each other rather than separate energy categories from each other.