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EMP HARDENING OF AIRCRAFT BY CLOSING THE POINTS-OF-ENTRY

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ABSTRACT

A cost-effective approach to keeping undesired radio-frequency energy out of aircraft is described, involving the use of wire-mesh, rf gaskets, improved bonding, filters, and ferrite cores. The concept is to make the fuselage of the aircraft serve as an electromagnetic shield against EMP by closing apertures and attenuating the currents on conductors which penetrate the fuselage from the outside.

Cockpit windows and circular viewing windows are closed using a few-mil diameter, blackened monel wire-mesh imbedded in the glass. Other rectangular viewing windows into the wheel well and looking aft were similarly treated.

Access doors are sealed with different kinds of rf gaskets. Mating surfaces are treated with special chem-films to inhibit corrosion. Corrosion tests were passed successfully.

Mechanical control shafts are treated by a variety of techniques depending on the criticality to safety, the size of the shaft, and the type of motion (translation, rotation, or both). Metal bellows large enough to follow the maximum stroke are used in some cases; ferrite cores, which reflect and absorb energy were used in others. Alternate designs using spring contract-fingers were also developed for some applications.

Special filter assemblies were devised to filter electrical cables entering the fuselage from the wings and empennage. The filter packages provide an rf barrier for mounting and use shielded cables to patch to the fuselage wall. Special connectors with conductive finishes were used.

Preliminary tests conducted before and after simulation of the point-of-entry (POE) closures indicate an overall attenuation of the average cable current inside the fuselage of about 30 dB. Repeatability of these results on a second aircraft was demonstrated. Investigations to date indicate that all of the major points-of-entry have been found and closed. The improvements achieved are believed to be of major consequence and were obtained at very low cost, with minimum impact on the system.

Introduction

There are many alternative ways to harden aircraft to nuclear electromagnetic pulse (EMP) effects, but conceptually these can be reduced to three basic approaches:

(1) try to keep the radio-frequency energy out of the aircraft,

(2) harden the electronics to withstand the signals that do penetrate,

(3) combinations of (1) and (2) above.

In a series of trade studies performed for the government,[1] it was concluded that to harden the C-130 aircraft it would be most cost-effective to begin by closing the points-of-entry (POEs)[2] into the fuselage. The trade studies indicated that this would provide the greatest benefit in improving hardness with the least impact on cost, weight, reliability, and maintainability. Based on this background, a detailed investigation was started to identify all the points-of-entry on the C-130, and to devise ways to close them. Hardware kits were subsequently designed and fabricated to support aircraft modification. Preliminary tests were performed to assess the probable benefit of closing the POEs. Results to date have been very encouraging, indicating a major improvement at very low cost. This paper presents the preliminary results of this on-going activity.

EMP Coupling Into Aircraft

The nuclear electromagnetic pulse (EMP) couples radio-frequency energy into aircraft cables by way of a series of interactions with the total system. The incident field interacts first with the overall structure, inducing a large transient current on the exterior of the vehicle (called skin current). This current, for aircraft, is usually in the order of 5000 - 10,000 amperes with a dominant frequency in the range of 1 - 10 MHz, determined by the dimensions and shape of the aircraft. The skin-current, and the associated charge density, leads to large scattered magnetic and electric fields outside the vehicle. The vector sum of the incident and scattered fields determines the total electromagnetic field outside the vehicle which, in turn, can drive or excite external cables or any holes or other openings in the structure. Energy which is conducted inside on cables or which propagates through the holes or apertures in the structure can result in other currents being induced on cables inside. From there, these currents can further propagate along the cables to critical or sensitive electronic packages where it may cause permanent damage, or transient upset. Fast digital circuits are the most readily perturbed or upset.

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[1]NAVAIR Contract N00017-74-C-0440

[2]Points-of-entry or POEs are defined as any points on the surface of an enclosure such as the fuselage where fields or currents enter from the outside.

Since there are many holes in a typical aircraft structure, there are many potential points-of-entry. However, the size of the opening strongly affects the magnitude of the fields coupled inside; for example, the magnitude of coupling through round holes is a function of the radius cubed. Thus, some holes can be ignored based on size. For cables which penetrate the skin of the aircraft and are exposed to the strong external fields, the pickup depends on length and geometry of the cables, their load impedances, and the distribution of fields along the cable. Because there are so many potential POEs, it is necessary to scope the effort to just close the major POEs. Certainly the riveted joints in the structure and the many small cracks in bolted sections will not be practical to close, and will limit the utility of closing other small holes. Nevertheless, there is appreciable benefit, as will be shown later, in closing the large holes and restricting the current on major cables.

Understanding the Effects of POEs

The current measured on a cable inside an aircraft, given some drive stimulus on the outside of the structure, is usually the net result of coupling from several POEs to that cable. The effect of each individual POE can be expressed in terms of a spectral distribution of radio frequency energy (or a linear transfer function). The total induced spectrum is then the sum of all the individual spectra. There is some experimental evidence that, in general, one POE is dominant in controlling the peak current on any given cable, but this is not always true.

If one POE is closed, the effects on cable currents inside the aircraft will depend on whether or not that POE was important to the measurement point of interest. Even if that POE was clearly dominant, the effect of closing that POE will only reduce the signal to the level of the next most dominant POE spectra. Thus, it is necessary to find all the major POEs, if significant improvements are to be realized.

As POEs are successively closed, the observed waveform at a particular measurement point inside the aircraft will, in general, decrease (or stay the same) in amplitude, but dominant frequencies will shift around, sometimes going to higher frequencies and sometimes lower ones. This is because the remaining open POEs may excite different dominant frequencies which may be higher or lower.

Finding the POEs

Since the goal is to close the large POEs, many are obvious because of their size. Cockpit windows, gaps around doors, and windows of any appreciable size are immediately suspect. Cables which penetrate the fuselage and go out into the wings, or the vertical and horizontal stabilizer are candidates. Many others, however, are less apparent.

Poorly bonded skin panels, control lines, hydraulic lines, pneumatic lines, de-icing systems, wheel wells, and mechanical shafts are also potentially important. Power lines which use the structure for a neutral return path may also be sources of EMP pickup.

Three tests were run on a C-130 aircraft to find the POEs. The first involved a visual inspection and a radio frequency "sniff test" in which an rf source was placed inside the aircraft and a detector was used outside the aircraft to sense points of leakage. The second and third tests involved simulation of EMP by injecting currents onto the exterior of the fuselage and measuring cable currents inside as the various POEs were closed.

For the C-130, the following types of things were found to be important sources of EMP coupling:

(1) Cockpit windows

(2) Cables in wings and empennage

(3) Fuel tank attachment points

(4) Cables under the radome in the nose

(5) Engine nacelle doors

(6) Personnel access doors

(7) Avionics bay doors

(8) Cargo loading door

(9) Windows

(10) Power return via structure

(11) Coaxial cable shield bonding

(12) Cables in nose wheel well

(13) De-icing lines

(14) Radar waveguide

(15) Mechanical shafts and control lines

Closing the POEs

Various techniques have been developed to close the POEs on the C-130. Some of these are:

(1) The use of a fine wire mesh in cockpit and other windows.

(2) The use of rf gaskets and special chem-film corrosion protection techniques around doors and access covers.

(3) The use of filters on cables that go outside the fuselage.

(4) The use of improved bonding on coax shields, waveguide, hydraulic lines, pneumatic lines, and some mechanical shafts.

(5) The use of ferrite cores around control lines and some mechanical shafts to absorb and reflect EMP transients.

(6) The use of a separate wire return for the neutral on power lines rather than using the structure.

(7) The use of shielding on some exposed cables in the wings, wheel wells, empennage and under the nose radome.

In essentially all cases, designs were possible without the need for expensive new tooling. RF considerations were simply integrated into existing designs and were readily adaptable to existing tooling. This was true for windows, and all of the door seals, for example.

Important considerations during the design phase were:

(1) Cost

(2) Reliability

(3) Maintainability

(4) Weight

(5) Life

(6) Optical performance (of windshields, for example)

(7) RF attenuation

(8) Flight safety

The current designs promise to meet the goals of the program.

Limited tests have been performed to verify the approaches taken. Corrosion tests have been performed on some rf gaskets and they passed long-duration salt-spray tests with no deterioration, due to the effectiveness of the chemical film treatment and the tendency of the gaskets used to seal out moisture.

Optical performance of the windshields was experimentally evaluated and was found to reduce optical transmission with the wire mesh in place by only 5 percent. (Glass alone reduces transmission by 20 percent.) Optical glare from the wire mesh was minimized by blackening the wires.

Filters were tested for surge current tolerance, and attenuation when operated into different load impedances.

Ferrite cores were evaluated during system level tests on the aircraft. Parameters of the cores were also measured in the laboratory.

The Results of System Level Tests

Two system level tests were performed on two different aircraft to demonstrate the potential benefit of closing the points-of-entry.

These tests were performed on aircraft parked on the ground, using a current injection technique to drive damped-sine currents onto the skin of the aircraft. Currents up to 400 amps were excited on the fuselage with three dominant pulser frequencies which were 300 KHz, 5 MHz, and 20 MHz, Magnetic and electric field measurements along the fuselage and wings verified that the excitation had about the desired spectral and spatial distributions.

Two aircraft were tested to verify that results would not be system-peculiar. There were minor differences, in particular cable currents inside, but overall the results for the two aircraft were remarkably alike.

Currents on about 150 points inside the aircraft were measured before and after the POEs were closed, waveforms were recorded using a Tektronix 465 oscilliscope, a camera with electronically actuated shutter and fast polaroid film (ASA 10,000). The oscilloscope was housed in a screen box. Triaxial cable was used between the screen box and the current probe (a Singer 91550-2 was primarily used). Voltages at the pulse-generator outside the aircraft were measured using a Tektronix 6015 voltage probe. Surface currents outside the fuselage were observed using a Genistron GSP-30 surface current probe. Magnetic fields inside and outside the aircraft were measured using the MGL 2D(A) sensor. Electric fields were measured using the HSD 2A(R). Permanent photographic records were made on approximately 40 of these points.

Prior to hardening, very large E-fields and H-fields were measured inside the aircraft and relatively large currents were observed on many cables. The statistical distribution of the peak values of the cable currents measured was found to be log-normal. Dominant frequencies noted covered a wide range from about 0.5 MHz to 100 MHz depending on the cable involved and the external drive dominant frequency.

The POEs were then closed using copper tape and aluminum foil, to simulate the effects of the wire mesh, rf gaskets, and cable shielding. Some cables were disconnected to simulate the effects of filters. Ferrite cores were used on selected control lines to reflect energy on those lines. Bonding was improved on wave guide and mechanical shafts. The power line neutral was disconnected from ground. Using these techniques, the major POEs on the aircraft were closed within a few hours.

The techniques used to close the POEs in these tests were simulations of the hardware being designed and thus cannot precisely indicate the benefit of the final hardware. Foil sheets used to close windows may work better than the planned wire-mesh, for example. However, in many cases the final hardware is expected to perform better than the simulations. The copper tape used to close door gaps, for example, could not be well bonded to the aircraft and was largely capacitively coupled to the skin. As a result, it is not likely to be as effective as a well bonded gasket. It was also not feasible to adequately simulate all of the ferrite cores planned on most of the mechanical lines which penetrate the fuselage.

Nevertheless, the net system improvement was appreciable.

Figure 1 shows the location of some of the major POEs of interest. There are other important POEs in the empennage, wheel wells, fuel tank attach points, and trailing edge of the wing, for example, which cannot be shown conveniently here.

The aircraft fuselage was driven with a damped-sine current pulse on the outside of the aircraft with three nominal frequencies as was noted before. The spectrum of the 5 MHz waveform is shown in Figure 2. The peak current distribution over the exterior of the aircraft is shown in Figure 3.

With this excitation, the common-mode current on cables inside the fuselage was measured before and after hardening. Figure 4 shows a histogram of the data prior to hardening (not all POEs were closed).

Analysis of all the data indicates a demonstrated reduction in the average current on all cables of about 20 dB using the simulated closure techniques. An extrapolation estimates that the final hardware will improve this to at least 30 dB below the unhardened case. It is believed that all the major POEs have been found.

A representative sample of the improvements derived from closing most of the POEs is shown in Figure 5. This diagram is developed by first ranking all of the measured peak-currents on cables from the largest (No. 1) to the smallest (No. 103) and plotting the peak current versus the rank number. It shows a considerable improvement in reducing cable currents everywhere. Although the graph does not show it well, there is general improvement, even for cables initially low in signal level.

Some Examples of the Hardening Techniques

Figure 6 shows a typical door seal which must serve both as a pressure seal and EMP seal. The EMP hardening was achieved by integrating a wire mesh into the design of existing door seals.

Figure 7 shows a typical rf-gasket installation on access panels.

Figure 8 shows a sketch of some of the flight control lines which go from the fuselage into the wings. Figure 9 shows a design for a ferrite-core EMP attenuator to reduce the current on these lines at the point where they penetrate the fuselage.

Figure 10 shows the elevator control shafts in the rear of the aircraft. Figure 11 shows a bellows arrangement for providing good rf-bonding to the fuselage. It also provides a pressure seal.

These are but a few examples of the techniques used to close the POEs.

The Penalties of Closing the POEs

All EMP hardening techniques have some associated limitations, disadvantages, or penalties. Closing the points-of-entry is cost effective because it utilizes an existing asset, the fuselage structure, to protect a large number of electronic packages which would be expensive to modify to withstand large EMP transients. Nevertheless, it has its price.

Closing the POEs on the C-130 adds some weight. Wire mesh and rf-gaskets add negligible weight, but cable shielding, ferrite cores and filters are not negligible. For the C-130 the gross weight is increased by about 0.03 percent. The largest part of this weight is in the filter packages for cabling coming into the fuselage from the wings and empennage.

The reliability degradation is, at present, believed to be negligible. The filters have the largest impact on reliability.

Maintainability is only affected to a minor extent, providing that adequate test methods are implemented for checking the effectiveness of the POE closures.

The life of the EMP closure techniques can only be estimated at this time. Wire-mesh window closures should last indefinitely. The ferrite cores should have no wearout problem. The metal bellows used for improved bonding of rudder and elevator push-pull shafts is guaranteed for 50,000 full-stroke cycles and would last much longer for normal operations, having smaller strokes. The filters have no wearout problem. The only limited life items are the door seals which will have a wearout problem. These seals must be periodically replaced and the mating surfaces periodically retreated with chemical-films for corrosion protection, but this does not appear to pose any real problem since they are readily accessible and easy to replace.

The cost impact, based on data presently available, indicates that it will increase the cost of the production aircraft by considerably less than one percent.

Studies regarding safety of flight indicate a negligible effect. This is partly due to the use of ferrite cores around critical control lines and fail-safe features of the ferrite packages.

The optical degradation of cockpit visibility is tentatively judged to be minor. Optical transmission is reduced from about 82 percent to 76 percent by the addition of the wire mesh, a negligible decrease. Other coatings used for de-icing, for example, degrade optical transmission by comparable amounts. Experienced pilots that have seen the new windshields generally express the opinion that it looks acceptable.

The Benefits of Closing EMP Points-of-Entry

Based on the evidence at hand, it appears that the systems engineer can expect to reduce the EMP coupling into electronics inside an aircraft fuselage by 20 dB to 40 dB by closing the major POEs; that is, that the average of all the currents on all the cables will be reduced by about that amount. The amount that should be expected depends on the size and the number of POEs in the unhardened aircraft. There is, it appears, a diminishing return in trying to achieve much more than that.

The effect on all the different cables is not the same everywhere. The biggest improvements tend to show up where the currents are largest inside the unhardened aircraft. Nevertheless, there is a tendency for all currents to decrease.

There are numerous benefits to this kind of EMP hardening in addition to the low cost and the minimal impact on weight and reliability.

First, it tends to mitigate the EMP environment incident on hundreds of electronic packages (both fields and conducted transients) so that the benefit is widespread. Virtually every package inside the fuselage experiences a reduced EMP stress.

Secondly, because the stress is reduced almost everywhere, the difficulty of adding further hardening is reduced. Filters, surge protection devices, coupling transformers and other hardening techniques can be made smaller, lighter, and lower in cost because the environment they must withstand is greatly reduced.

Thirdly, some troublesome non-linear effects are eliminated. For example, during the C-130 tests prior to hardening, arcing was heard and seen across door gaps. Arcing can occur many other places at high levels of excitation. Electronic packages can also be highly non-linear when driven by high-amplitude EMP transients

Any arcing creates noise over a wide band of frequencies and makes EMP hardness assessment much more difficult. Highly non-linear load-impedance variations of the electronics also make assessment difficult. Thus, by closing the POEs, the system is made to respond to EMP in a more linear manner which simplifies and lowers the cost of EMP hardening and EMP hardness assessment.

Another significant benefit of closing EMP points-of-entry is that it can reduce the electromagnetic interference levels inside the aircraft from sources outside, either from on-board emitters or nearby emitters. It may also significantly improve the survival during lightning strokes.

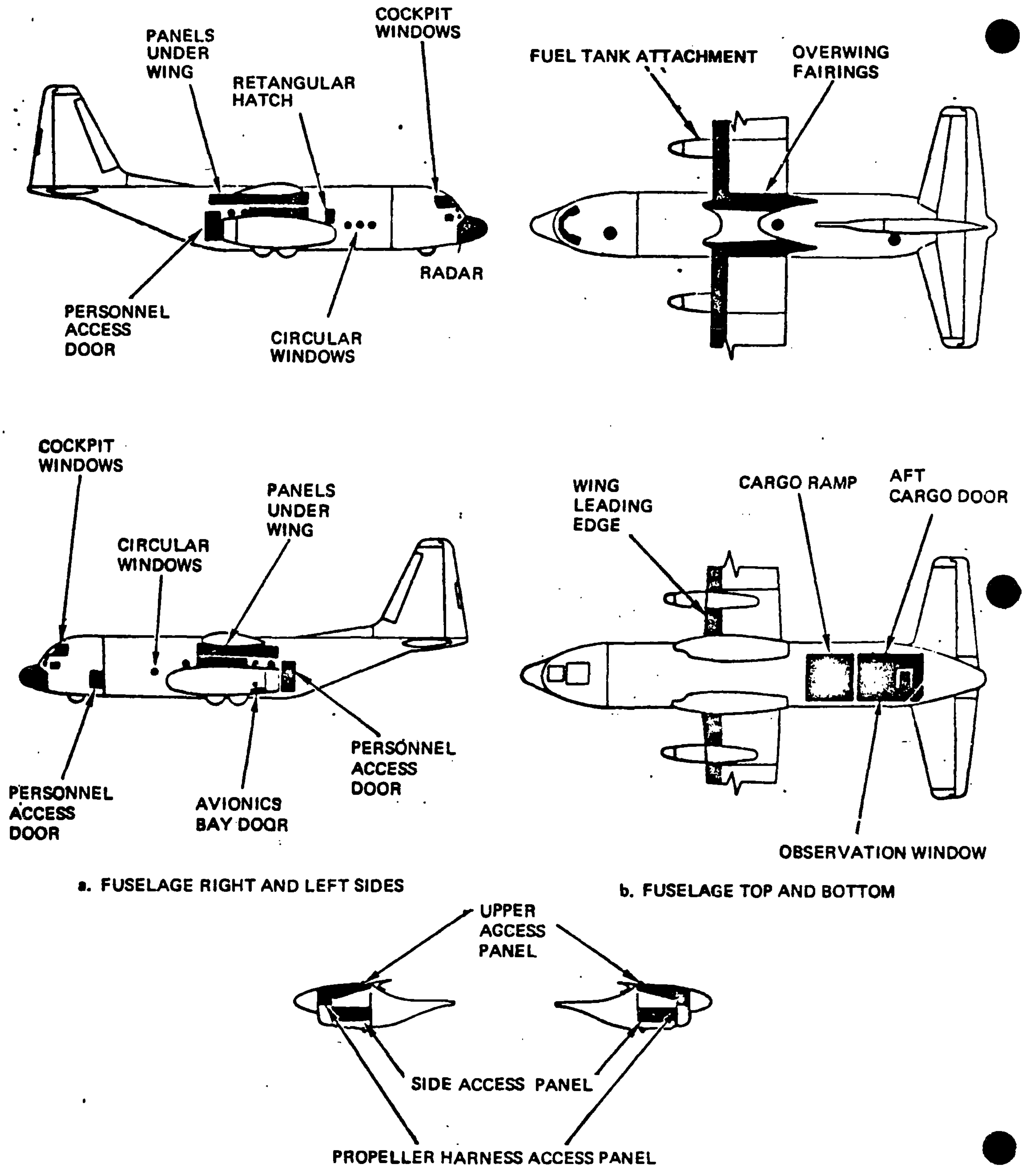
Closing the POEs is also a good approach for sequentially hardening existing aircraft. Other layers of hardening can be added later in a cost-effective, sequential manner, which also makes the EMP hardening program easier to manage.

Although the present efforts are continuing and the final evaluations are not yet complete, the indications are at present that closing the EMP points-of-entry on aircraft is a most effective first step in hardening systems to EMP.

References

1. C. Baum, Ed., Electromagnetic Pulse Interaction Notes, Air Force Weapons Laboratory Publication AFWL 3-1, 3-2, 3-3, 3-4. June-October 1971.

2. G. E. Morgan, G. T. Smith, R. V. Whiteley, Rockwell International Report Number C75-168.1/201, April 11, 1975, Classified Report.



a. FUSELAGE RIGHT AND LEFT SIDES

b. FUSELAGE TOP AND BOTTOM

c. ENGINE ACCESS FAIRINGS

Fig. 1. Location of Primary Points of Entry

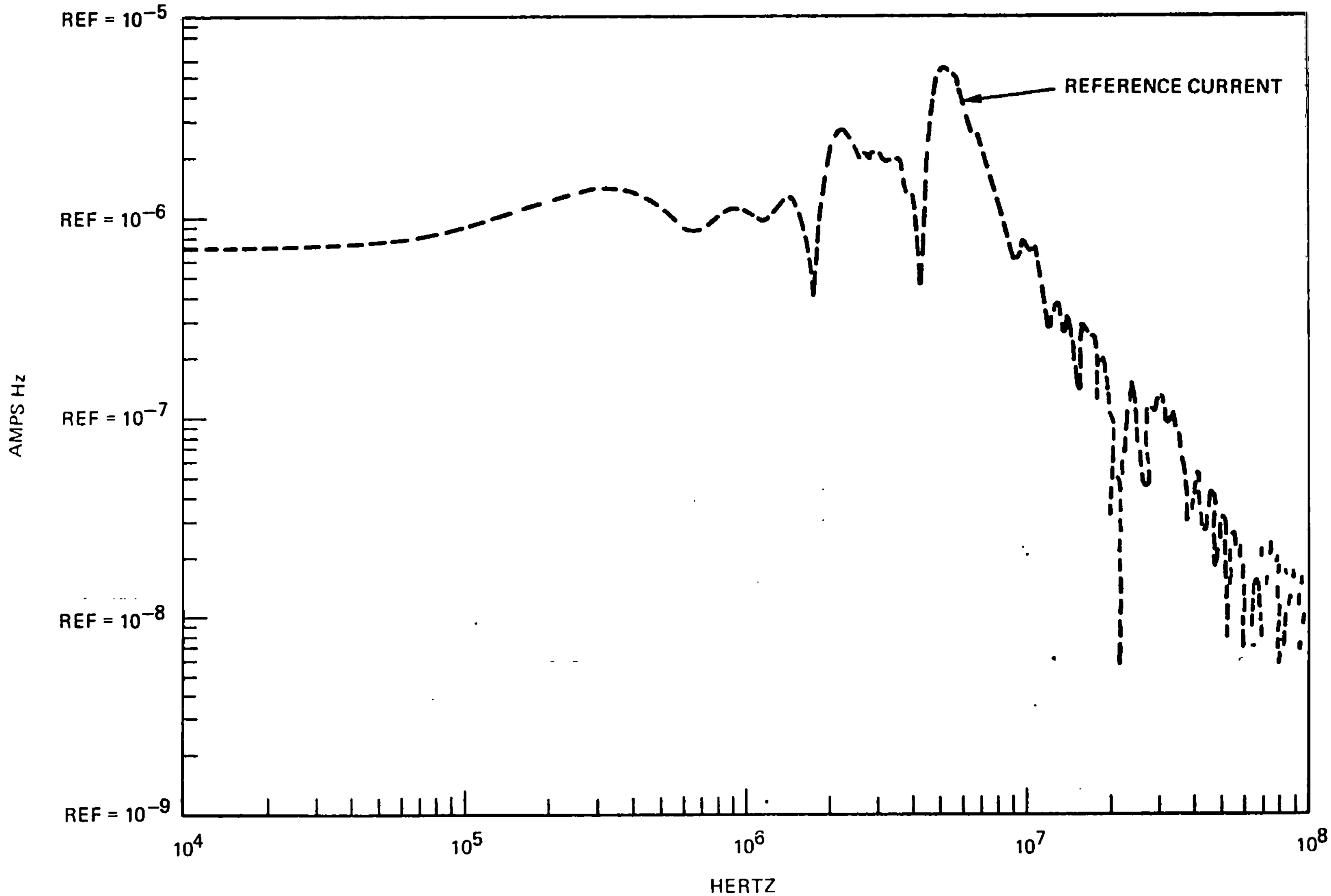


Figure 2. 5 MHz Baseline Reference Current

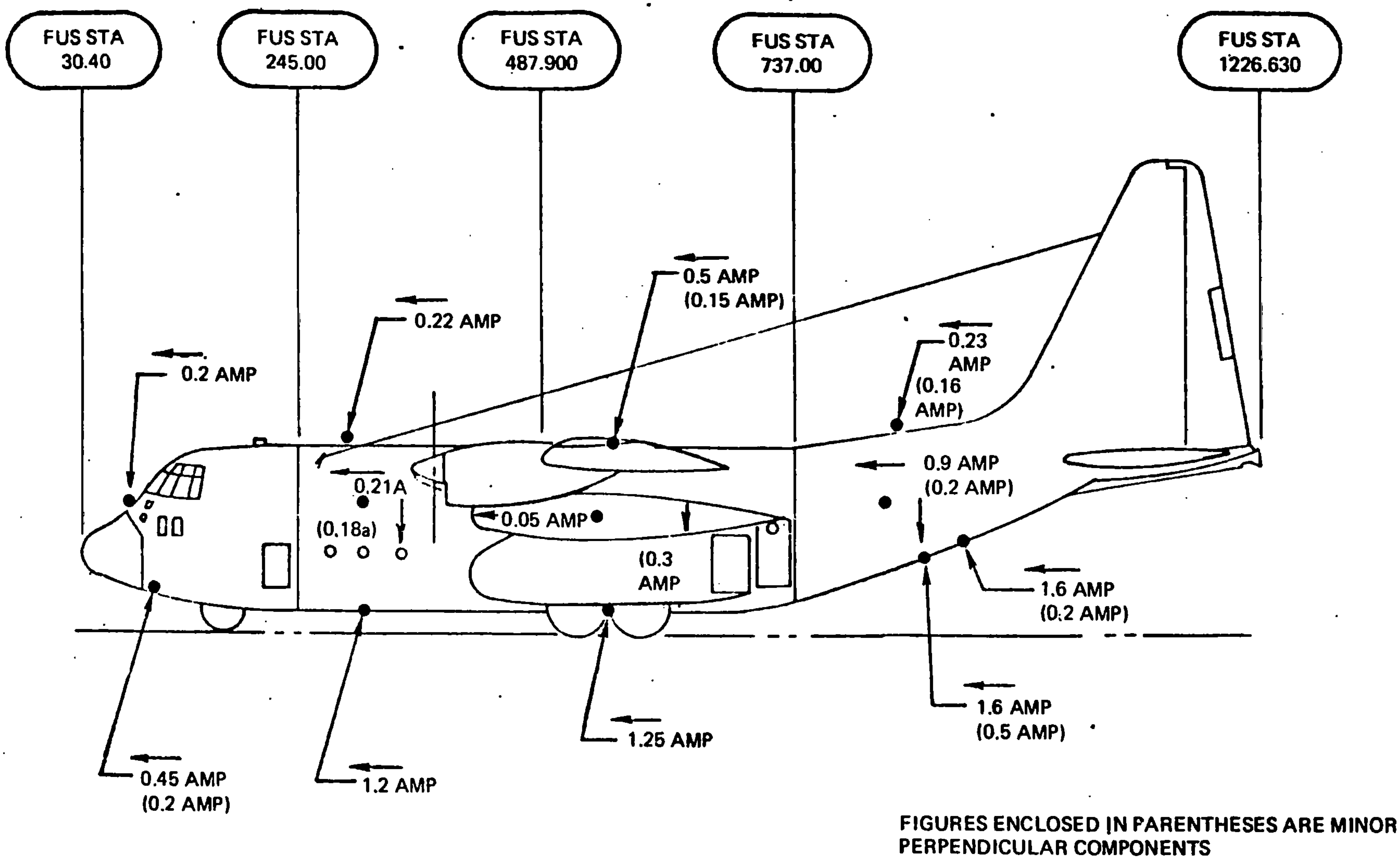


Fig. 3. Skin Current Measurement Results, Side View of Aircraft

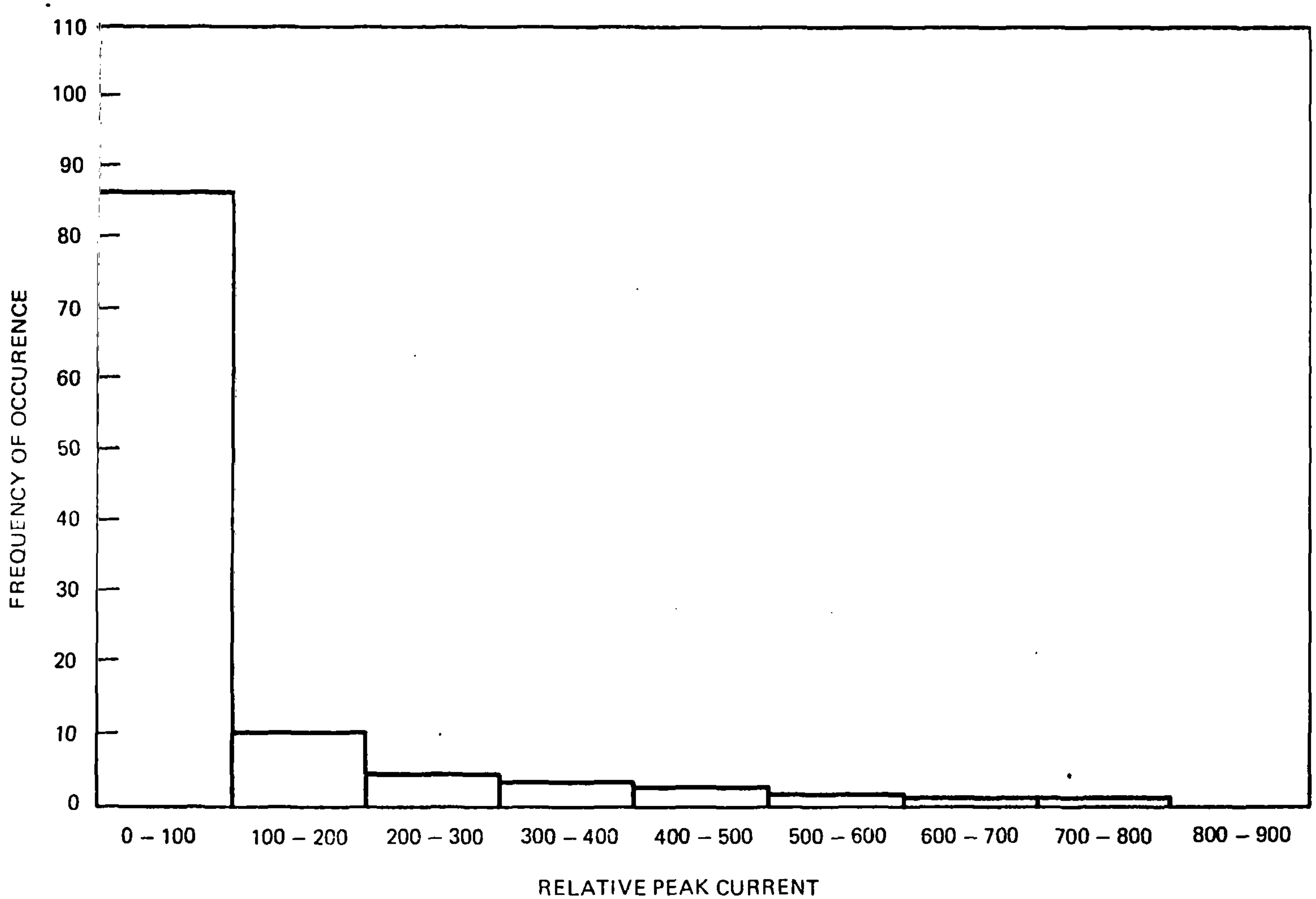


Figure 4. Histogram of the Measured Currents Inside the Aircraft from Simulated EMP Excitation at 5 MHz

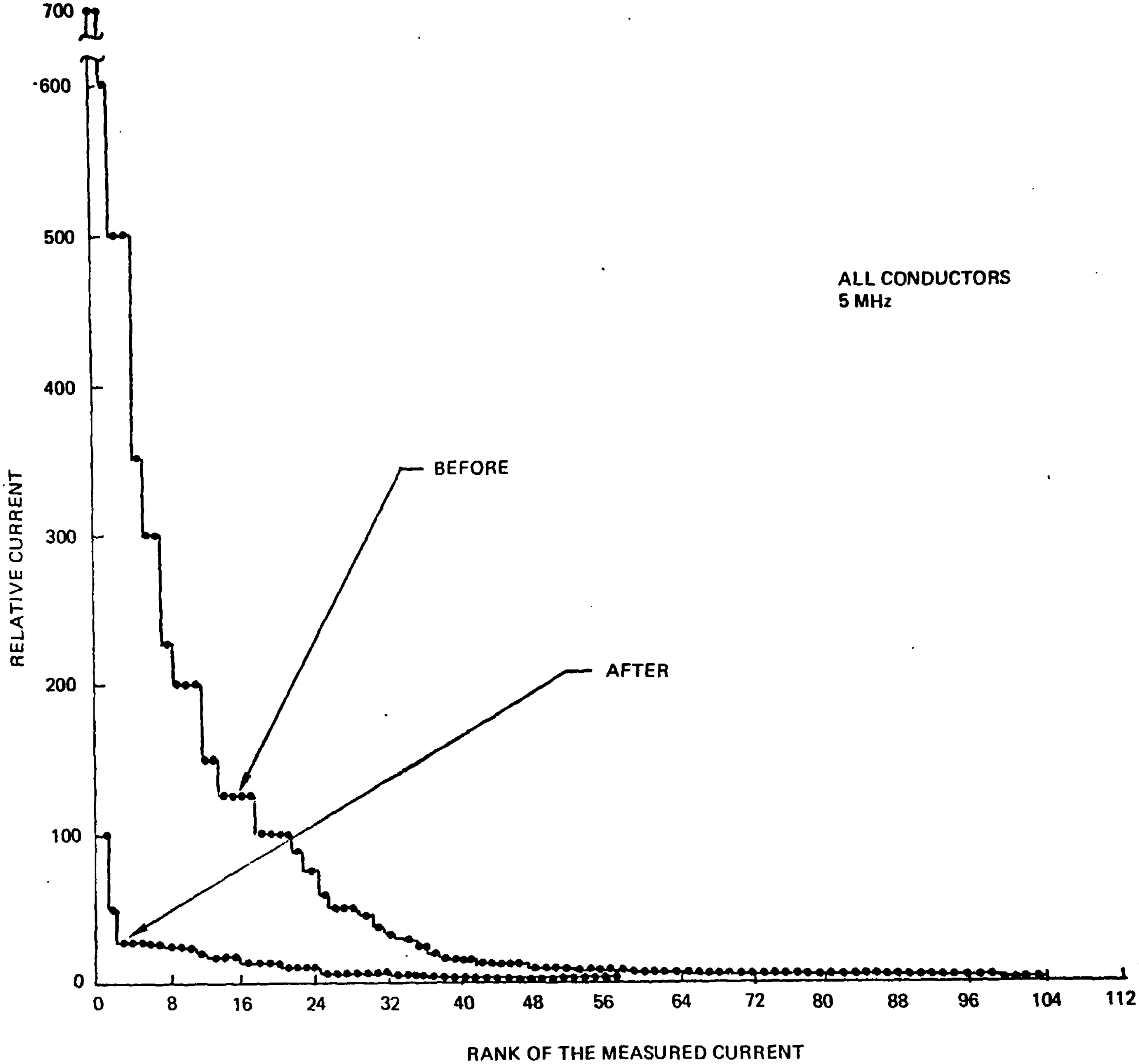
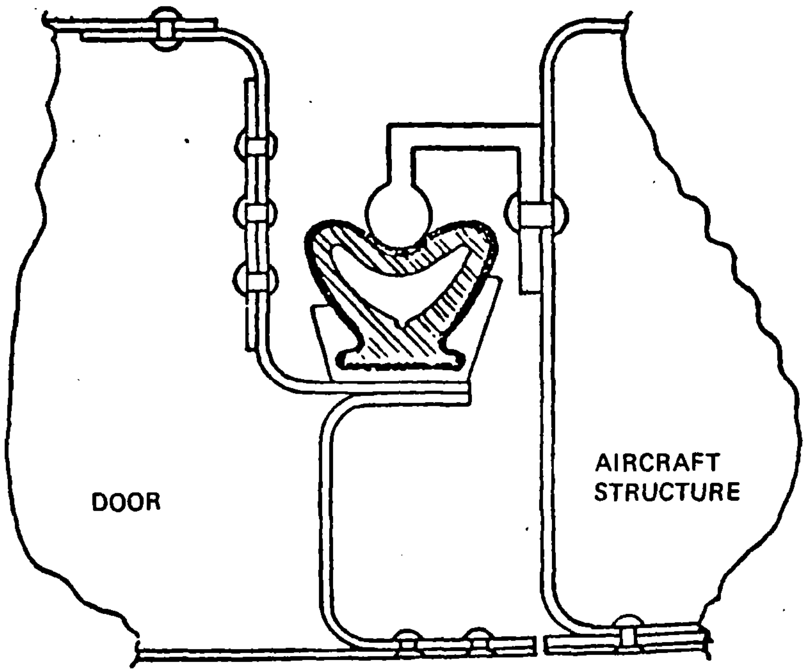


Figure 5. Linear Comparison of All [illegible]ents (Including Non-electrical Elements) Before and After [illegible]rtial Hardening



EXAMPLE – CREW DOOR

Fig. 6. Door Seals

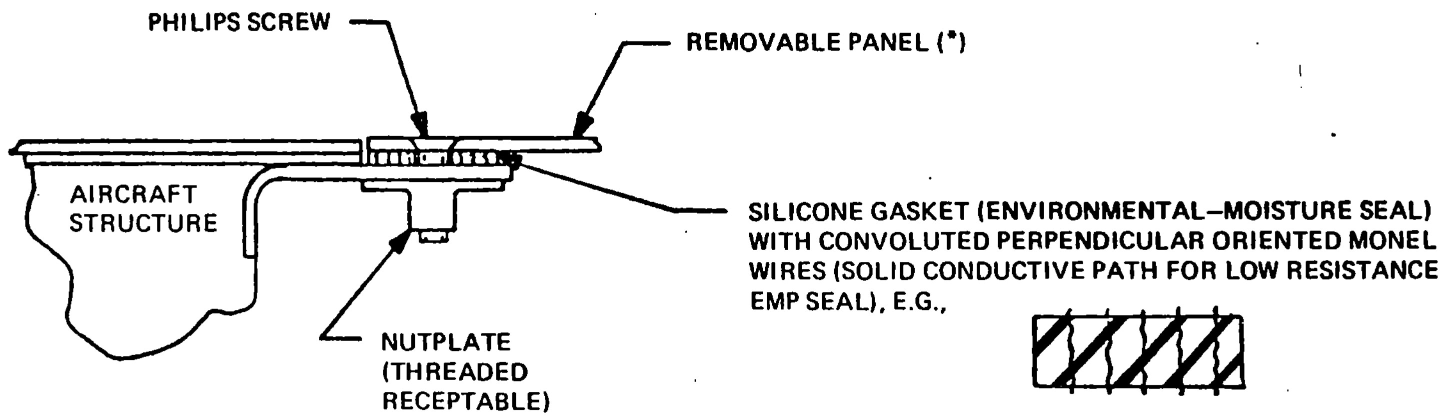


Fig. 7. Access Panel Seals

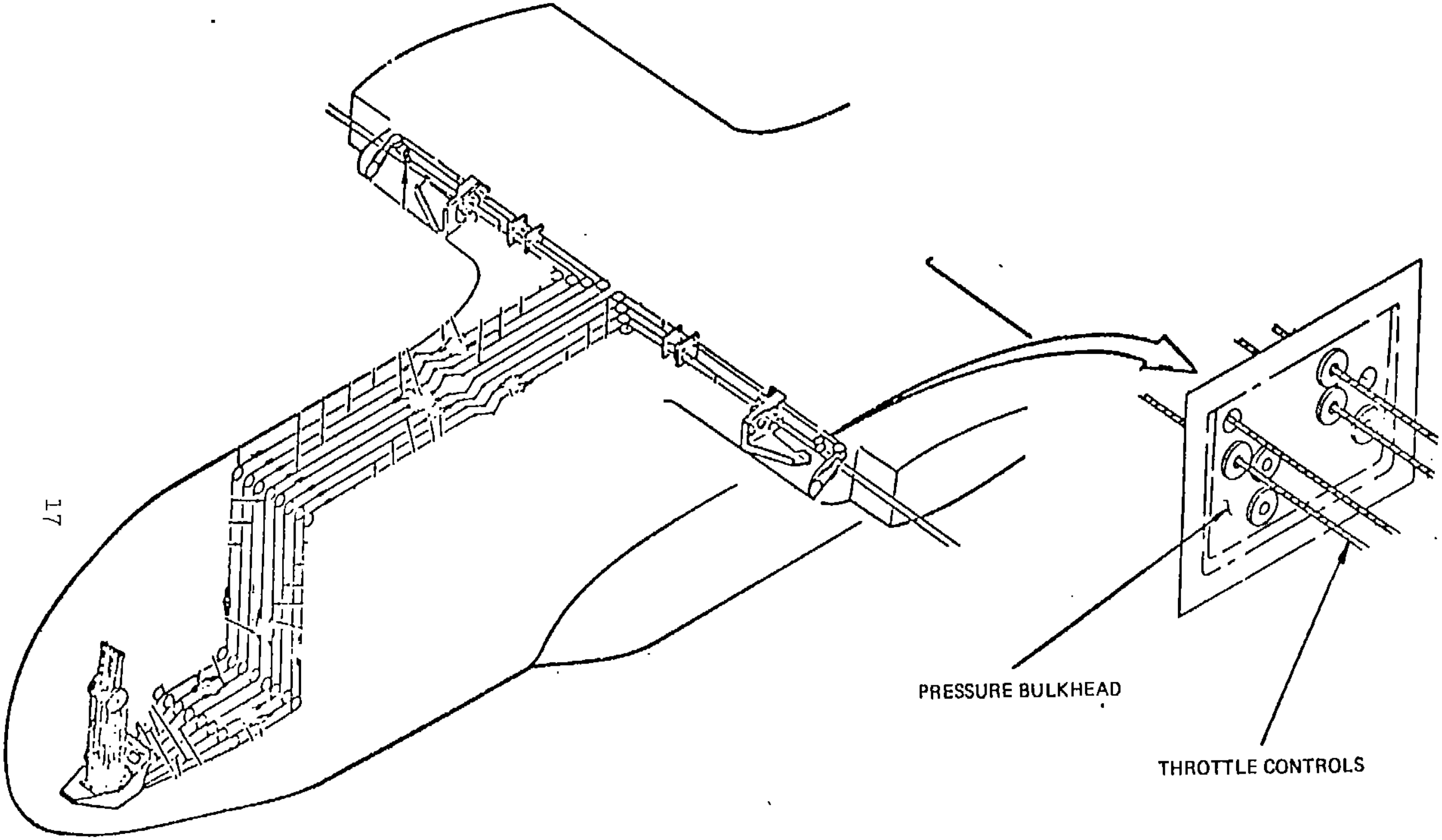


Fig. 8. Engine Control and Condition Lines

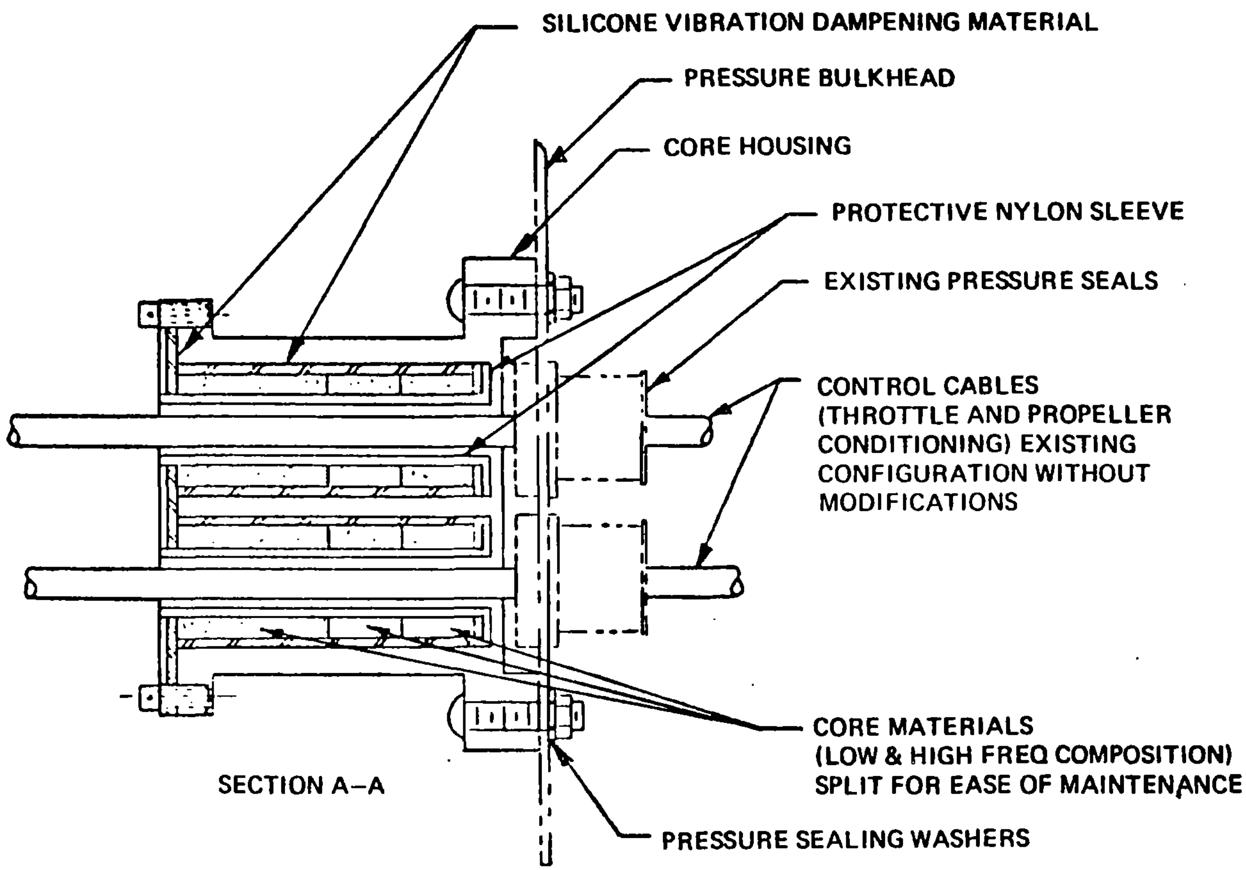


Fig. 9. Ferrite Core EMP Attenuation

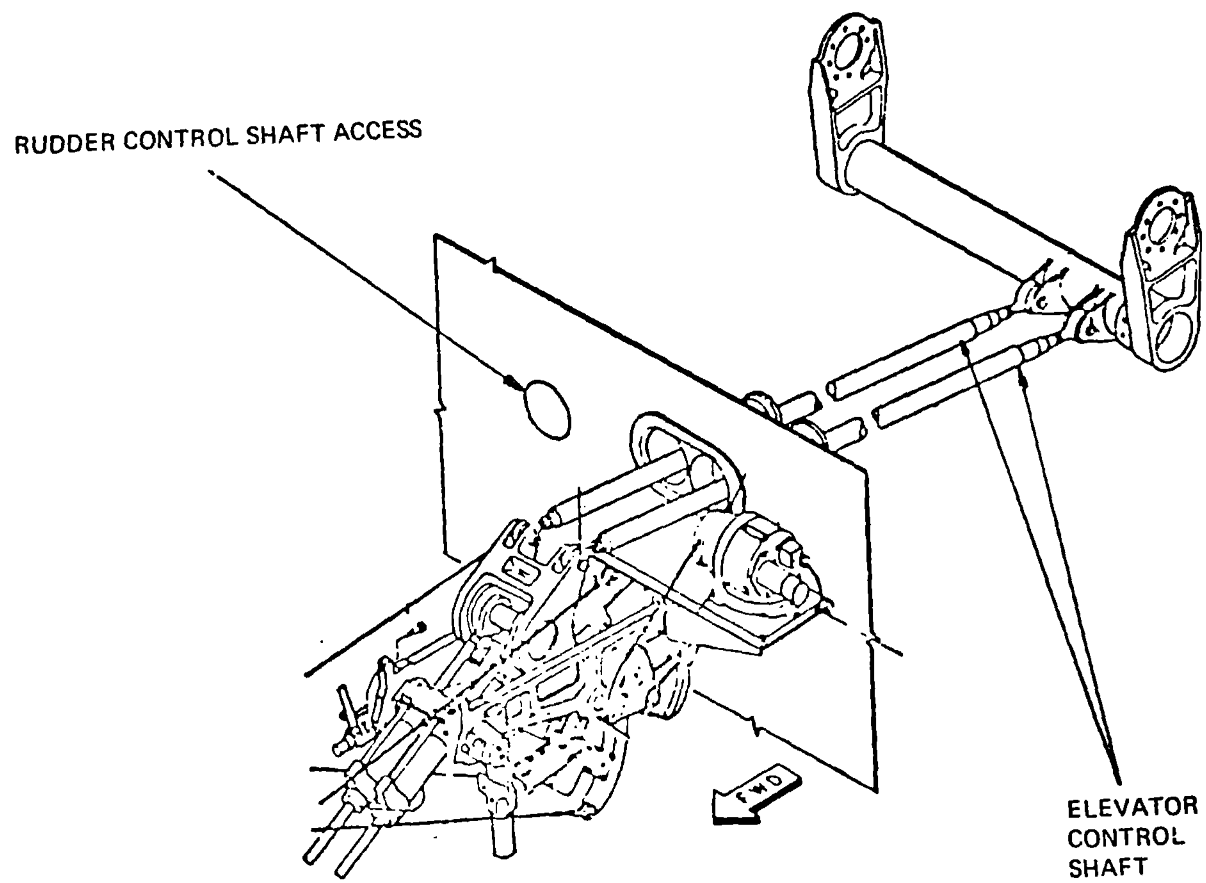


Fig. 10. Elevator Controls

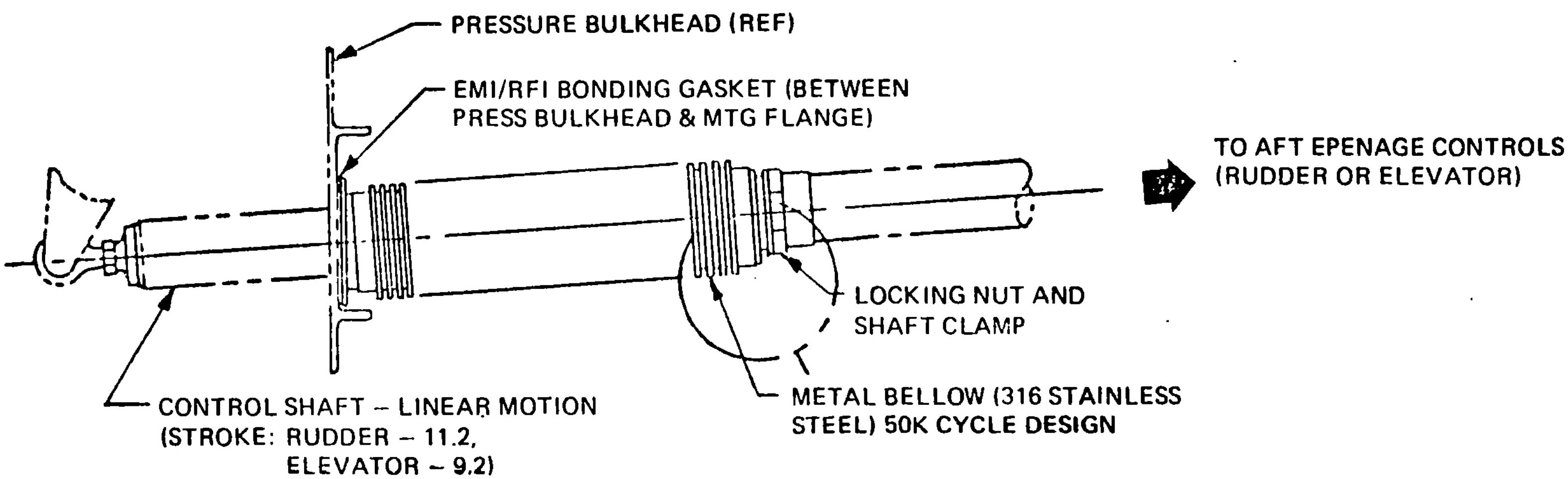


Fig. 11. EMP Bellows