RFI/EMC SHIELDED CONSTRUCTION SYSTEMS METHODS AND EVALUATION

The subject of this article is RF Shielded Room Construction. Rooms also are known as "Faraday Cages," "Screen Rooms," "Screen Shielding," "Electrostatic or Electromagnetic Shielding," or just plain "Shielding," as it is generally called today.

An RFI/EMC shielded enclosure basically consists of highly conductive metallic barrier completely surrounding a given space. This room has two functions: it either keeps electromagnetic energy in or out. Typical examples for the first application are secure communication and conference rooms; for the second are rooms used for calibration of electronic systems or medical electronic instrumentation. This paper discusses the effectiveness of these enclosures and provides a guide to their proper construction, assembly and testing.

Shielding Spectrum

Shielded enclosures are effective in varying degrees over a large part of the electromagnetic spectrum from DC through microwave frequencies. In practice, most RF shielded enclosures are defined by their ability to shield over that portion of spectrum in which transmitting and receiving instruments operate. Except for special low frequency magnetic rooms, this means from 10 KHz to 40 GHz. The shielding effectiveness or performance of RF shielded construction systems is expressed in decibels and is called attenuation. The dB relationship is a logarithmic function expressed in microvolts.

Performance requirements are established by directly relating the ambient electromagnetic background noise and electronic instrumentation compatibility and sensitivity. Attenuations up to 120 dB at the frequency range mentioned previously are possible with a relatively simple construction system, utilizing inexpensive metallic materials. Therefore, a practical way to select a shielded enclosure is to specify shielding effectiveness between 100 and 120 dB at a frequency range from 10 KHz to 10 GHz, and sometimes up to 40 GHz.

Materials Selection

Fundamental equations governing the design and computation of shielding effectiveness determine the selection of conductive material for construction of the enclosure and thickness of this material. Shielding effectiveness is the total capability of a given material to prevent propagation of electromagnetic energy, and it is represented schematically in Figures 1 and 2.

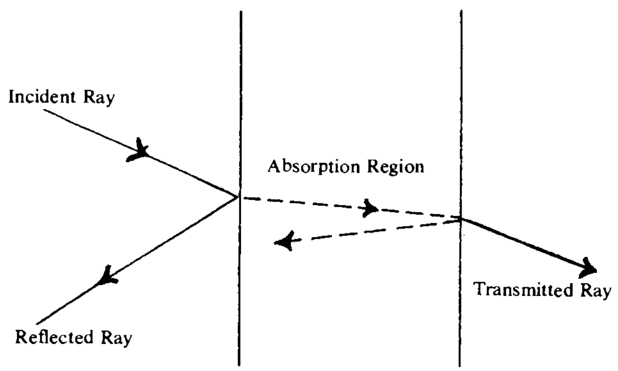


Figure 1: Reflection and Attenuation

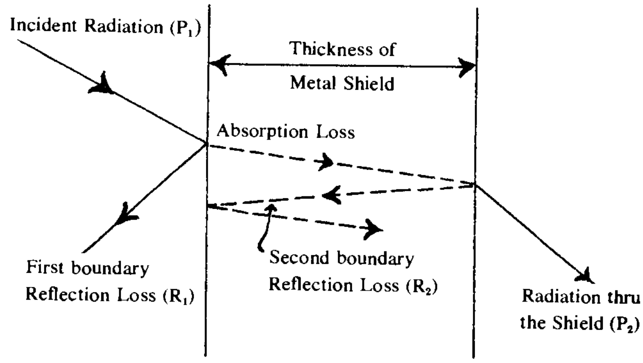


Figure 2: Factors Contributing to Total Shielding Effectiveness

Reflection and absorption losses are a function of frequency, thickness of shielding material, resistivity, permeability and conductivity. Reflection loss is caused by a difference in characteristic impedance between the incident field and the shield and may also vary with distance. When the impedance of the incident field is much higher or lower than the impedance of the shield, the reflection loss is very high.

At all frequencies, magnetic fields are low impedance and electric fields are high impedance. Generally, for most materials, the impedance is low at low frequencies and high at high frequencies. Therefore, magnetic reflection loss R_h is small because there is a good match between the impedances of field and shield. For this reason, magnetic shielding depends primarily on absorption loss. For good shielding effectiveness ferromagnetic materials are the most suitable, and as the frequency increases, the impedance mismatch widens with the consequent increase of R_h.

Electric fields are readily stopped by metal shields because high reflecting loss RE is easily obtained due to the mismatch between field and shield is always large.

The total reduction in field intensity is caused by reflection and absorption losses. Therefore the shielding effectiveness of an enclosure is the sum of reflection and absorption losses. Reflecting takes place at the surface of the shield, while absorption is the dissipation of the signal as it passes through the body of the shield (refer to Figures 1 and 2). Because of these factors, absorption governs in designing the proper shield. To compute the thickness of the shield or to compute absorption of the shield (if thickness is known), the following equation is used:

$$A = 3.338 \times 10^{-3} \times t \sqrt{Gf\mu} \text{ dB}$$

wherein

t = thickness of shield in mills of inches.

G = relative conductivity referred to copper to be equal 1, .61 for aluminum and .17 for iron.

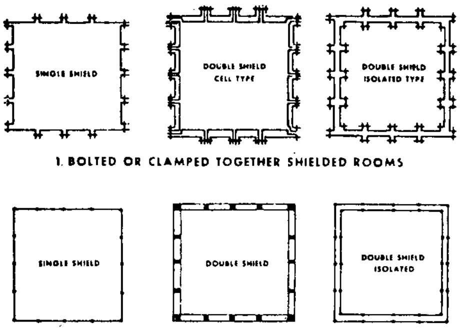
μ = permeability of free space = 1.26×10^{-6} henrys/meter, approximately equal 120 π/V where V is speed of light in free space, equal 3×10^{8} meters/sec.

f = frequency in Hz.

Actually, the spectrum ranges from 10 KHz to 10 or 40 GHz. To obtain a shield between 100 and 120 dB, the thickness of the steel will be between 24 and 26 gauge. This logic leads us to the concept of a welded steel tank without openings, utilizing materials as stated above. This will produce an excellent shield. The problem is to adapt this welded steel tank to working people who will require mechanical services, egress and power. Steel happens to be the least expensive metal for this purpose. Naturally, the best engineering design is based on cost-effectiveness.

Planning Phase

The RF shielded room is an electromagnetic attenuator and as such can be designed like any other electronic circuit. Like other attenuators, there are parallel methods and each has its relative advantage and disadvantage. Given companies use these principals to determine what is best for a given application, based both on the technical and the cost requirements.



ALL SEAM WELDED SHIELDED ROOMS

Figure 3

All shielded rooms, facilaities etc. known today can be illustrated as shown in Figure 3.

As shown, there are two broad types of these shielded rooms: the bolt or clamp together, modular shielded room; and the all-welded shielded room. Each has its relative merits of performance versus dollars and life cycle.

Before the design is attempted, a simple set of planning rules must be followed as follows:

1. Required Minimum Shielding
   - Specification and Standards
   - Maximum Allowable RF Ambient
2. Physical and RF Electromagnetic Environment
   - Indoor or Outdoor Installation
   - Building Codes
   - Frequency, Sources, CW-Pulsed EMP, Other
3. Shielding Material Properties
   - Electric Fields
   - Magnetic Fields
   - Plane Wave Fields
4. Discontinuities
   - Seams
   - Vents
   - Doors
   - Power Lines
   - Etc. as Shown in Figure 3
5. Test and Acceptance
   - Specifications/Standards

Having established the requirements, planning etc., the next step is to solve the particular design problem on hand by generating a complete engineering package for construction of the facility. This design must be based on shielding design as stated below and also must include architectural, structural, mechanical and electrical aspects of the proposed facility.

Shielding Design and Equations

The following equations are presented in a simplified form as an aid in designing RF shielded enclosures. All terms used are defined:

SE = Shielding effectiveness, representing reduction of electromagnetic energy in (dB). Measurements are made in power, voltage or current ratios.
R = Total reflection loss in (dB) from both surfaces of the shield.
A = Absorption loss inside the shield.
B = Positive or negative correction factor in (dB) (omit when A is more than 10 dB).
Z_s = Intrinsic impedance of the shield.
Z_w = Wave impedance of incident wave in space.
μ = Relative magnetic permeability referred to free space: 1 for copper, 1 for ferrous metals at microwave frequencies, and 200 to 1000 for ferrous metals at low frequencies.
μ_o = Permeability of free space = 1.26×10^{-6} henrys/meter.
ξ = Permittivity of free space = 8.85×10^{-12} farads/meter.
G = Relative conductivity referred to copper (1 for copper, 0.61 for aluminum, 0.17 for iron).
V = Speed of light in free space = 3×10^8 meters/second.
f = Frequency in hertz/second.
λ = Wavelength in meters/hertz.
β = $2\pi/\lambda$
ω = $2\pi/f$
r = Distance from source to shield in meters.
r_1 = Distance from source from shield in inches.
t = Thickness of shield in mils.
T = Thickness of shield in meters.
E = Electric field component in volts/meter.
H = Magnetic field component in amperes/meter.
p = Plane wave.
α = Attenuation coefficient of metal in nepers/meter.

$\sqrt{\frac{\mu_o}{\xi_o}}$ = Impedance of plane waves in free space = 377.6 ohms, approximately 120π

To compute R:

$$R = 20 \log_{10} \left[\frac{(Z_s + Z_w)^2}{4 Z_s Z_w} \right] \text{dB} \qquad \text{eq.(3)}$$

$$Z_s = \sqrt{\frac{\mu f}{G}} \times 3.69 \times 10^{-7}$$

Values of R may be zero, positive or negative. In all cases R is positive at frequencies above 1 Khz. SE is always positive and in all cases greater than zero.

$$Z_w = \frac{E}{H} = \frac{I}{V\xi} = 376.7 \text{ ohms for high impedance electric fields, when } r > \lambda \qquad \text{eq. (4)}$$

$$Z_w = -\frac{E}{H} = V\mu_o = 276.7 \text{ ohms for low impedance magnetic fields, where } r > \lambda \qquad \text{eq. (5)}$$

To compute R for magnetic fields the given formula reduces to:

$$R_{(H)} = 20 \log_{10} \left[\frac{0.462}{r_1} \sqrt{\frac{\mu}{Gf}} + 0.136\, r_1 \times \sqrt{\frac{Gf}{\mu}} + 0.354 \right] \text{dB} \qquad \text{eq. (6)}$$

To compute R for Electric fields the given formula reduces to:

$$R_{(E)} = 353.6 + 10 \log_{10} \left[\frac{G}{f^3\, \mu\, r_1^2} \right] \text{dB} \qquad \text{eq. (7)}$$

To compute R for plane waves, where $r > \lambda$ the given formulas reduce to:

$$R = 108.2 + 10 \log_{10} \frac{G \times 10^6}{\mu\, f} \text{ dB} \qquad \text{eq. (8)}$$

To compute A:

$$A = 3.338 \times 10^{-3} \times t \sqrt{Gf\mu} \text{ dB} \qquad \text{eq. (9)}$$

To compute B:

$$B = 20\log_{10} \left\{ 1 - \left[\frac{Z_s - Z_w}{Z_s + Z_w} \right]^2 \times 10^{-A/10} \times \left(\text{Cos. } 7.68 \times 10^{-4}\, t \sqrt{Gf\mu} - j \text{ Sin } 7.68 \times 10^{-4}\, t \sqrt{Gf\mu} \right) \right\} \text{ dB} \qquad \text{eq. (10)}$$

NOTE: If A is more than 10 dB. B is neglected.

FREQUENCY	IRON		COPPER		ALUM.	
	G	μ_a	G	μ	G	μ
60 Hz	0.17	1000	1	1	0.61	1
1 KHz	0.17	1000	1	1	0.61	1
10 KHz	0.17	1000	1	1	0.61	1
10 KHz	0.17	1000	1	1	0.61	1
150 KHz	0.17	1000	1	1	0.61	1
1 MHz	0.17	700	1	1	0.61	1
3 MHz	0.17	600	1	1	0.61	1
10 MHz	0.17	500	1	1	0.61	1
15 MHz	0.17	400	1	1	0.61	1
100 MHz	0.17	100	1	1	0.61	1
1 GHz	0.17	50	1	1	0.61	1
1.5 GHz	0.17	10	1	1	0.61	1
10 GHz	0.17	1	1	1	0.61	1

Construction Methods

The shield must be made of sections and the sections must be joined together. Welding, brazing, soldering or a mechanical joint system can be used for joining. Regardless of the joint method, there must be a complete system which will complement new or existing building construction, thus enabling the installatin of doors, ventilation, ductwork, windows, electrical power distribution — with architectural finishes inside or outside, computer type raised floors, etc.

In order to meet this challenge, the industry which produces RF shielded enclosures has introduced different joining methods and other components. Shielded room users should pay attention to the following points:

1. Almost all metals can provide much more attenuation in theory than in practice.
2. The key to high performance is not choice of materials, rather a tested shielding system of good design and workmanship in handling all joints, all openings, and all discontinuities of any type.
3. Of all such openings, the door is the most critical. The effectiveness of the entire room — regardless of size or materials of construction can be degraded significantly by one improper opening.

Joining Methods

Soldering: Soldering is not a mechanical system (it could be referred to as a conductivity type of joint) and does not have any structural properties. Normally, soldering costs are high because it is a very slow process. If a soldered joint is used, then a mechanical fastener must be introduced for structural support.

Mechanical Joining: The RF shielding industry produces different mechanical joint systems which mostly consist of rolled steel sections. In order to select the proper joining system, attention must be paid to the interface between the panel and actual joint. Panel tolerance must compliment the joint tolerance. The joint must be a rolled steel section protected against any possible oxidation by plating.

The other major component is the structural RF panel, a lamination of two steel layers around a solid core material. Normally this is a commercial product produced for building construction or for construction of inexpensive truck bodies. Attention must be paid to all details in order to assure RF effectiveness due to shrinkage or poor workmanship.

In order to achieve a good and positive RF joint, structural RF panels must be produced to strict quality control specifications. Materials must have established tolerances, and must consider the thickness of zinc coating, moisture contents in the core material, proper adhesive, and proper tolerance for overall thickness. By achieving a uniform thickness of RF panels, the mechanical joint will make a positive surface contact to produce a tight RF seal at every connection point.

Welding or Brazing: Welding is another method of joining steel plates. This is an expensive method since a considerable amount of quality control must be introduced during the welding process. In addition, steel thickness must be increased. It is impossible to weld 24 gauge steel and eliminate warpage. Because additional weight is added by increasing steel thickness, and high labor rates apply in welding, the total cost of the shield will be substantially higher in comparison to mechanical joining. However, sometimes a welded shield is desirable in a very large shielded enclosure.

If EMP is a consideration in the use of the enclosure, probably a welded structure will give better results. The main problem with welded enclosures is that they are field assembled; therefore quality control is extremely difficult and expensive. Moreover, there is a limited number of skilled welders to weld RF shielding joints, a task quite different from welding structural joints. In structural joints the consideration is stress or structural quality. In RF welded joints, one is concerned with electric continuity without any pin holes, thus, a different technique must be utilized.

Complete System

Regardless of the joining system or material chosen, consideration should be given to the complete system, rather than a welded or bolted box. The main components are the door, filters, wave guide vents, wave guide mechanical penetrations, windows, set-up panels, etc. A short discussion of all these components follows:

RF Door: This is the most important component in a shielded room. It is the only movable part with a high frequency of usage. Depending upon the shielded room's function, the door could be of a regular 3'x7' size, or a large door to permit entry of large components for testing. Doors 50'x50' in size are not uncommon. The ability to manufacture a long lasting shielded door requires experience and know-how, whether it be a manual or fully automatic, electrically operated door. Functionally, a door can be a swinging door or a sliding door.

Sliding doors normally will depend on metal-to-metal contact. The mating surfaces are plated. This metal-to-metal contact is the most reliable means of sealing. Dirt, dust and grease can collect around the edge of the door opening or door perimeter which will substantially degrade the structure's attenuation; therefore, maintenance is very important.

The best RF door is a properly designed swinging type door. The design is critical to door rigidity, RF contact mechanism, means to compress this mechanism, and proper hinges, in order to maintain the door in factory-established closing or opening tolerances.

Mechanical Penetrations: Ventilation is an important feature in any room. Air should be fed through wave guide type vents. Improperly installed wave guide vents can be a source of serious RF leaks. A vent should always be provided with a collar for duct attachment if parent room air is used. Mechanical penetration for plumbing and heating are fed into the room through wave guide type penetrations. A good RF shielding system should have all these mechanical components available for any possible services.

Electrical Penetration: An electrical penetration is a wire which carries the desired electrical energy to or from the room without permitting spurious signals from being carried through the enclosure wall. The electrical penetrations, therefore, include a filter. These filters are bilateral devices designed to pass the fundamental frequency voltage and current, while at the same time preventing all radio frequency energy from entering or leaving the enclosure. Internally, the filter contains capacitors and inductors designed to comply with the electrical requirements of the system.

Filters used on shielded enclosures usually are of low pass type and must be provided for all electrical lines such as power, telephone, teletype, paging system, etc. Rating of the filter must be equal to the rating of the enclosure. Normally it will be between 100 and 120 dB over the frequency range of 14 KHz up to 10 GHz. If the enclosure is designed above 10 GHz, special extension assemblies must be added for the higher frequencies.

Proper filter installation is a vital function because at the point of penetration substantial leaks could develop. Normally, filters and all associated hardware should be installed by the room manufacturer to assure system integrity.

Room Assembly And Grounding

A well designed system installed under skilled supervision will provide good performance, but an improperly installed system regardless of design and care exercised, will not perform. The system must be installed under full and continuous supervision of an expeienced supervisor. During erection, care must be exercised to clean all joining members and panels with a special cleaning fluid. Complete dimensional alignment and shimming (as required) must be introduced in the parent room floor in order to assure squareness and levelness of final installation. Once the room is installed, it should have a grounding stud. The complete room should be grounded only at one point to a positive earth ground.

Testing And Final Acceptance

Electromagnetic interference cannot be seen, smelled or touched. Therefore, testing of RF shielded environment must be a prerequisite in order to assure pure signals during different procedures. Normally, a shield must be tested after installation and before any finishes are applied but after all electrical systems are in place. It is desirable to conduct a second test after all wall, floor and ceiling finishes are in place and just before the room is ready for occupancy. It is a good practice to re-test the room at least once a year.

Every test must be performed using established test procedures based on standards. All tests should be performed in accordance with an approved test plan showing the test frequency, specific test points and required performance at each test frequency. Two test standards currently used are MIL-STD-285 and NSA 65-6. MIL-STD-285 does not cover the complete spectrum; it calls for one reading at each wall at very limited test frequency. Using this standard will not establish the quality of the room, if the room is specified up to 10 GHz, or below 100 KHz.

In order to assure a room's shielding effectiveness, new standards must be established which should incorporate full test frequencies, including test at 10 GHz and also test at all penetrations including around the perimeter of the door. Regretfully, we do not now have this type of test standard. For this reason, a test plan is extremely important. Test procedures can be utilized as stated in MIL-STD-285 by extending the frequency range.

In conclusion, it is quite possible to obtain from a shielded room an attenuation of 120 dB at full frequency range and to maintain it at peak performance. To accomplish this, it is important that the work be done exclusively under the engineering and field supervision of an expert. All components should be designed to be part of a complete RF shielding construction system. In this way, there is only one responsible party with an established reputation to achieve and fully guarantee this high performance. (See Figure 4).

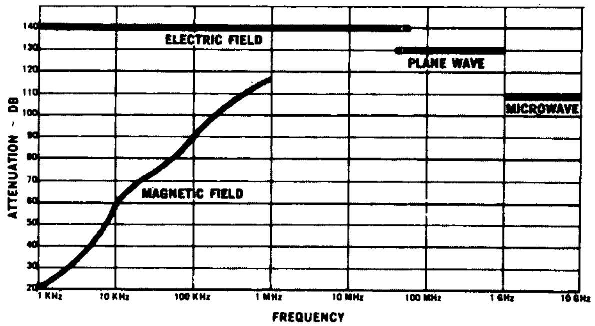


Figure 4

Shielded Structures For EMP

Today, we are faced with new phenomenum known as "EMP", which has an entirely different design criteria for the shielded structure. Application is to keep the EMP energy from entering the shielded enclosure and effecting equipment reliability. EMP protective measures include proper bonding, grounding, methods of placement of various protection devices and shielding of installations. This paper will confine itself to shielding installation problems.

Early testing of nuclear weapons revealed the existence of electromagnetic fields generated by nuclear detonations. As more information, experience with more varied test conditions and better theoretical calculations were available, it became increasingly apparent that EMP was potentially destructive to an electrical system.

A nuclear electromagnetic pulse (EMP) will produce two general categories of effects which can result in faulty operations of electrical/electronic apparatus, permanent damage to particular kinds of components and cables, and in some cases, pose a serious shock hazard to personnel:

1. Radiated electromagnetic fields which are best reduced at an installation by proper metal shielding.
2. These fields induce large conductive surge currents on power, telephone and other lines and metal conductors entering the installation. These surge currents can in many cases be suppressed by proper limiting devices or filtering.

This paper will deal with the first category which is the radiated electromagnetic fields.

The electromagnetic pulse is in a form of energy which lies within the "radio frequency spectrum", ranging from powerline frequencies to radar frequencies.

Incorporation of EMP protection into all new facilities that must communicate with others during or after a nuclear event should be considered during the early stages of the design. Protective requirements shold be incorporatd during the original design stage from economical point of view.

The portion of the facility that houses EMP sensitive, critical equipment, should be enclosed with a proper shield providing the EMP shielding requirements sufficient to protect the equpment.

A preliminary step in a program to protect existing or new facilities against EMP is to examine available construction drawings and specifications and make a determination of the construction materials used. For example, if the construction is typically reinforced concrete, determine the diameter spacing, or extent of reinforcing steel and whether any portion of the steel bars were welded or brazed at joints and intersections. A limited amount of shielding from radiated fields will be provided by having electrically bonded reinforcing steel as part of the basic structure. Burial of the structure will provide additional reflection and penetration losses, depending upon the earth conductivity and dielectric constance. The utilization of building construction techniques cannot be expected to provide more than a nominal 20 dB of shielding against EMP and should be disregarded in the total calculation for shielding requirements.

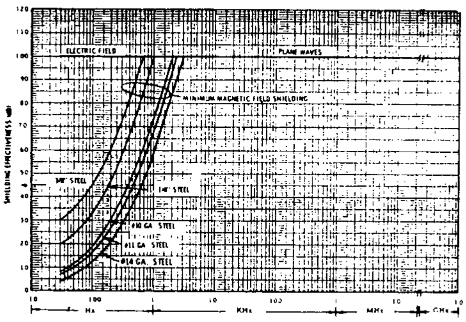
There are three basic methods to provide the shield:

1. Modify existing building materials.
2. Provide proven welded RF metallic liner.
3. Provide proven prefabricated structural RF system.

Method 1

Any continuous steel plates will also provide shielding and should e considered as part of the EMP protection inherent to the structure. The use of additional shielding may be required in certain areas. Whenever feasible, overall building shielding is preferred to room or area protection. The exterior of the building can be provided with an RF/EMP liner continuously welded and secured to the structural steel elements to provide the required shielding protection. External to this liner, insulation and building siding finish can be attached in a conventional manner.

As simple as it appears to be, the basic method #1 is not recommended because shielding quality control cannot be exercised every step from beginning of the construction until final completion without excessive labor costs. Furthermore, should any RF deficiencies of the system be found during final testing, pinpointing the leak or leaks would be a most difficult task and any repair would entail considerable rework. Assuming full quality control, shielding effectiveness of this method is approximately 25% less as compared with Methods 2 and 3. (See Figure 5)



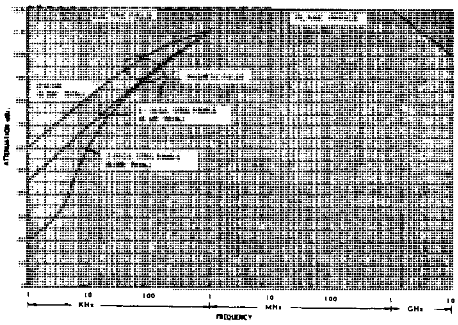
MINIMUM SHIELDING EFFECTIVENESS OF LOW CARBON STEEL WALLS

Figure 5

Method 2

A proven RF welded system is not simply welding two plates of steel together. The welding must be done under direct field supervision of an expert in RF welded shielding construction. The weld must be of the low temperature MIG type and proper selection of welding rod must complement the shielding performance desired. A continuous weld is produced without the introduction of foreign material in the weld.

Structurally integrated shielding system is unique since it minimizes the structural supporting elements by incorporating them in the panel configuration and thereby offers a low cost shielding system of high performance, ideal for computer facilities or large areas, and full performance. (See Figure 6)



PERFORMANCE CHARACTERISTICS OF TYPICAL COMMERCIAL SHIELDED ENCLOSURES (WALLS: LOW CARBON STEEL) --ATTENUATION VS FREQUENCY

Figure 6

Combining the structural support with the shielding panel configuration reduces installation time, shipping weight and maximizes the available space shielded. All components are readily acceptable by this sytem. Doors, filters and other penetrations combine to offer a complete facility.

Welded rooms can be constructed to any room configuration with no limitations. Attachment to the parent room is minimized and in most cases rooms are built free-standing. Since the intergral structural supports can be located internally, attachment of electrcal work etc., does not penetrate the shielding.

The structurally integrated shielding system also provides weather proof facilities for mobile or outdoor requirements.

This system represents the ultimate in the state-of-the-art of shielding design and can be built to suit any physical configuration regardless of how complex. In many instances large structures are built as a combination of free-standing and attached to present building construction. There are cost savings involved, utilizing the existing structural steel which can be analyzed to afford the customer the most economical approach.

Method 3

Proven prefabricated RF system, will provide performance per Figure 2 at lowest cost. All materials selected and details developed are only for one purpose, to maintain RF integrity for the life of the building where the shielded rooms are installed. This construction will not degrade and will provide 120 dB attenuation up to 10 GHz, and 100 dB attenuation above 10 GHz.

This article was prepared for ITEM by Ralph Aronson, shielded room consultant, and president of Ralph Aronson and Associates, Stamford, CT.

APPENDIX A

Typical photographes of RF shielded rooms

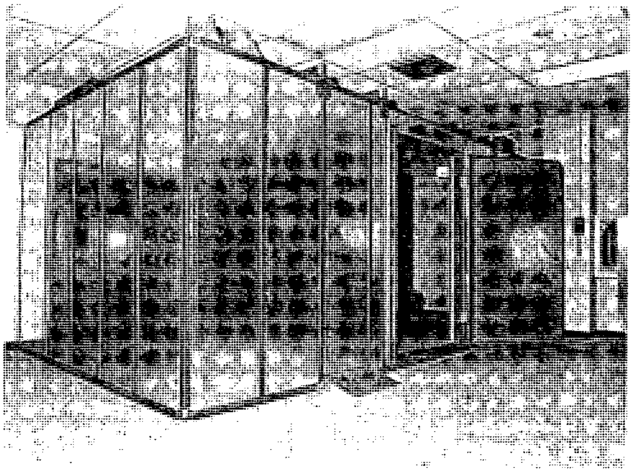


FIG. A: PREFABRICATED MEDIUM SIZE CLAMP-TOGETHER RF ROOM USED IN MEDICAL RESEARCH, *COURTESY KEENE CORP.*

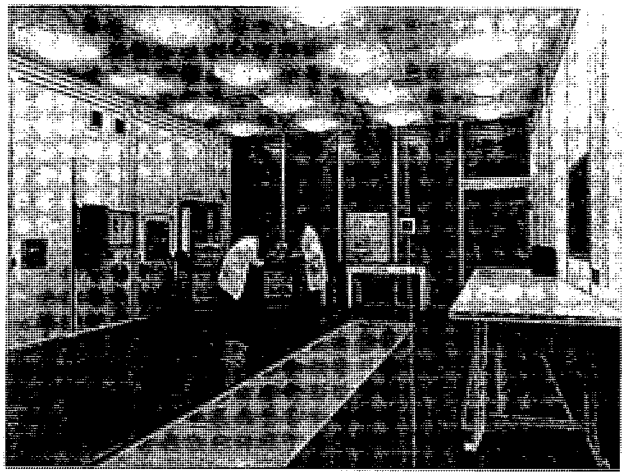


FIG. B: INTERIOR VIEW INTO PREFABRICATED LARGE CLAMP-TOGETHER RF ROOM USED FOR EMC TESTING, *COURTESY UNIVERSAL SHIELDING CORP.*

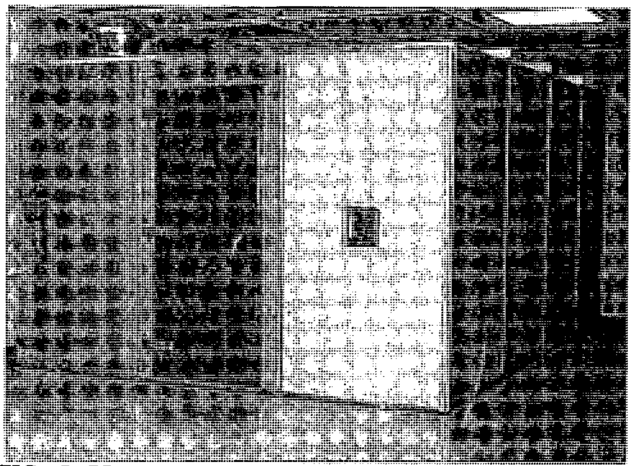


FIG. C: PREFABRICATED STOCK SIZE MODULAR ROOM USED FOR INSTRUMENT CALIBRATION, *COURTESY UNIVERSAL SHIELDING CORP.*

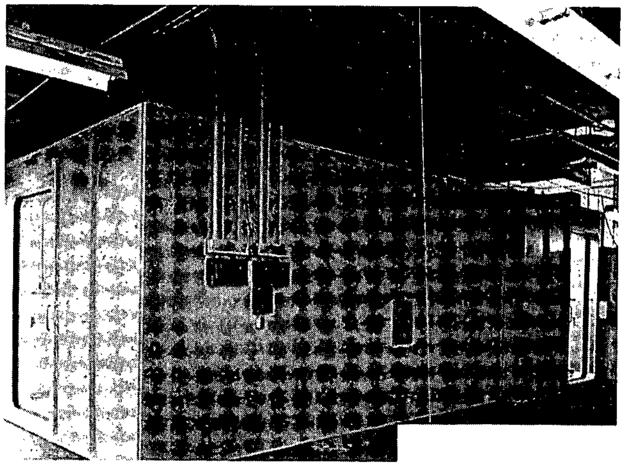


FIG D: ALL-WELDED DUAL SHIELDED ROOM, 3/16" THICK STEEL; RED/BLACK ISOLATION BETWEEN ROOMS, *COURTESY LECTROMAGNETICS, INC.*

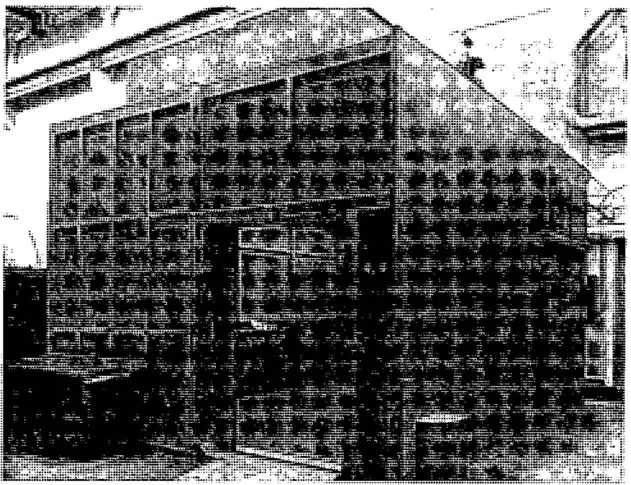


FIG. E: WELDED RF SHIELDED STRUCTURE WITH A SLIDING DOOR, USED FOR TEMPEST TESTING, *COURTESY LECTROMAGNETICS, INC.*

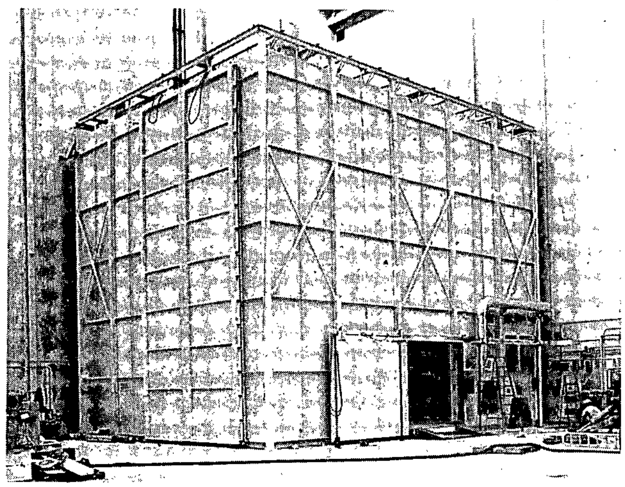


FIG. F: WELDED LARGE RF STRUCTURE WITH REMOVABLE SIDE WALL SECTION, USED FOR EMC TESTING, *COURTESY KEENE CORP.*