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REVIEWS

# Polymer Matrix Composites for Electromagnetic Applications in Aircraft Structures

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**Abstract |** The paper gives a short technical appreciation of some of the critical requirements of polymer composite materials in aircraft structures, beyond their well known specific strength/stiffness driven applications. In this regard, it focuses on certain important electromagnetic properties of the composites commonly used in aircraft structures, with specific references to microwave transparency, electromagnetic interference (EMI) shielding and microwave absorption applications. The paper presents a short theoretical overview on each of these applications and narrates the status of research and development activities pertaining to these domains.

## 1 Introduction

### 1.1 *Prologue*

This paper is an attempt to narrate the developments of polymer matrix composite materials for different types of electromagnetic applications in the aerospace discipline by describing their past, present and possible future status. The descriptions in the 'past' sections have been generally restricted to the activities till the end of 20th century. Since most of these developments have already migrated from the realms of laboratory R&D and research papers to that of established technologies and industrial practices, they can today be considered more of popular science knowledge. Since these past developments should today be treated more as a part of the composite materials folklore, they have been described generically only without any specific citations. However, the formal reference indexing in the order of their citations have been done for the more 'present' (Year 2000 onwards) developmental findings.

It may also be noted that each of the specific topics related to the subject matter discussed in this paper can individually qualify to be the contents of an entire volume and the attempt to accommodate all of them within a single paper with sufficient levels of clarity is both highly optimistic and audacious. In this light, the paper will at best try to present a flavour of each of the topics to the readers with a few slices of specific literature studies, and will never attempt towards or claim for its exhaustivity.

### 1.2 *Rise of composites*

While materials and related technologies are broadly credited for defining and redefining the human civilizations across the ages, the composite materials in particular are believed to have started building their niche for roughly about the last 3000 years of history. One of the first conscious uses of composites can be traced back to the year 1000 B.C., when straw reinforced clay composites were used to manufacture bricks for constructing residential dwellings. In a far more recent development in the 1800's, once again the composite materials in the form of steel rods reinforced concrete/cement stole the show, thereby leading to another quantum leap in civil and construction engineering. The last century was characterized by cellulose/glass fiber reinforced resin composites, which were initially used for certain automobile parts. But the advent of carbon and aramid fibers and their composites with epoxies and polyimides propelled these materials to high performance applications like those in aerospace from 1970s onwards. Thereafter, the refinement in composite technologies in terms of high performance matrices, high strength/modulus fibers and improved process engineering have ensured a bullish application curve for these special materials till today.

A closer look at the above growth story of composites, however, reveals an interesting fact. Across the ages, the predominant uses of these lightweight materials have been largely restricted to applications demanding high specific mechanical properties only, though in some cases,

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they have found their utilities in electrically/thermally insulating applications as well. Superior mechanical performances of these composite materials have always tempted the structural designers, especially from aerospace industry, to embrace them and replace the traditional metallic components in the systems. However, the metallic structures, in spite of their weight penalties, used to come with some intrinsic advantages like electrical conductivity (ideal ground plane for on-board electronics), electromagnetic interference (EMI) shielding, static charge dissipation etc., which were otherwise mostly conspicuous by their absence in the traditional Fiber Reinforced Plastic (FRP) materials. As a result, the smiles and satisfaction of the structural engineer started coming at the cost of systems/integration engineers for any aerospace project. Perhaps, this phenomenon partly explains the relative unpopularity of FRP materials among the electrical engineers, which has eventually restricted the expansion in the more diversified adoption of these materials. However, off late, when each gram of additional weight is measured by its value in gold for most aerospace projects, expanding the scope of these composite materials is indeed the need of the hour.

### 1.3 *Expanding scenario*

This expanding scenario has necessitated an active collaboration between the electrical and materials technologies and technologists. While the electrical engineer is being forced to weigh the major gains as compared to the minor problems associated with these FRPs, the materials designer is being forced to understand the electrical and electromagnetic compulsions and realities of the multifunctional systems, to improvise accordingly and improve their materials to meet the challenges and achieve the best of the both worlds. The expanding scenario has taken the concepts of microwave transmission, shielding and absorption (each of which will be elaborated in subsequent sections) within the folds of material designs. Besides, other issues like static discharge, lightning protection, electrical grounding etc. are also gaining prominence within composite applications, but have not been discussed in the present paper. During the last decade or two, these requirements have opened up a whole new and hitherto less explored branch of materials research, namely composite materials for electromagnetic applications.

### 1.4 *Scope of the paper*

The present paper is an attempt to briefly capture historical developments in this particular school of research, i.e., composite materials for electromagnetic applications. A short introduction to the understanding of the electromagnetic (EM) wave—material interactions with the aid of few basic EM equations have been provided as a starter. Thereafter, major thrust areas in the subsequent sections involve the *Past*, the *Present* and the *Future* of materials' development for microwave transmission, shielding and absorption applications. Efforts have been made to include some of the typical R&D activities and results from the relevant fields, but this paper should only be treated as a representative collection and does not claim to be exhaustive in any way.

## 2 EM Wave Fundamentals

### 2.1 *EM spectrum*

Figure 1 depicts the entire gamut of the electromagnetic spectrum. It must be understood that the present discussions will mostly be restricted to frequencies ranging from hundreds of kHz to tens of GHz (i.e. Radio and Microwave Frequencies).

### 2.2 *EM wave—material interactions: The possibilities*

Consider an EM wave of a defined frequency incident at the interface of a foreign material (Medium-2) inserted in its original medium (Medium-1) of propagation, say air (Refer Figure 2). Intuitively, we can say that there are three different phenomena, one or more of which may occur thereafter, viz.

1. Transmission of the wave through the material
2. Reflection of the wave from the interface
3. Absorption/attenuation of the wave within the material

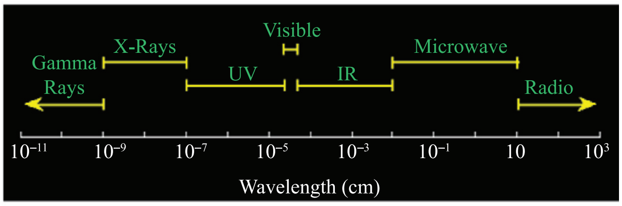


***Figure 1:*** The electromagnetic spectrum.

Drawing parallels with visual optics for more clarity, we can understand that while the first phenomenon is a criterion for a transparent material, the second is a feature of a mirror, whereas the third is a characteristic of a black body absorber. In microwave domain as well, the predominance of each of these interactions dictates the usability of the materials in any particular microwave environment/application. The subsequent EM theory discussions will help in quantifying these requirements in terms of material properties and geometries.

## 2.3 *Basic electromagnetic equations*

Whenever an EM wave is normally incident on a foreign medium, the two basic mechanisms of reflection and transmission are known to be governed by the following equations:

$$R = (\eta_2 - \eta_1)/(\eta_2 + \eta_1) \tag{1}$$

$$T = 2\eta_2/(\eta_2 + \eta_1) \tag{2}$$

where

$R$ = Reflection coefficient,
$T$ = Transmission coefficient, &
$\eta_i$ = Complex impedance of ith medium, which is given by:

$$\eta = [j\,\omega\mu/(\sigma + j\,\omega\varepsilon)]^{1/2} \tag{3}$$

where

$\eta$ = Complex impedance of the medium,
$\omega$ = Angular velocity of the wave,
$\mu$ = Magnetic permeability of the material,
$\sigma$ = Electrical conductivity of the material, &
$\varepsilon$ = Dielectric constant of the material.

**Complex impedance:** Hindrance offered to the propagation of electromagnetic wave by a medium, complex function of medium's electrical and magnetic properties.

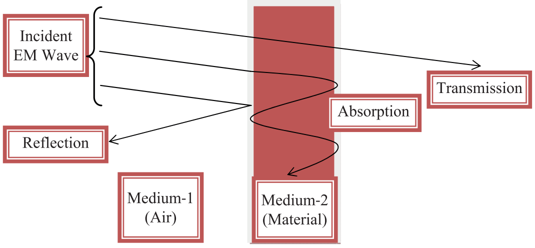


***Figure 2:*** EM wave material interactions.

For oblique incidence, the basic principles and trends remain the same, except for an introduction of trigonometric coefficients in terms of the angle of incidence. The above equations can be easily analyzed to arrive at the listed observations (Refer Table 1).

The above discussions throw some light on the reflection and transmission behavior of the materials which will be helpful later for understanding the design concepts for the composites for EM applications. Some more common simplifications of these equations under specific circumstances will be introduced later in the appropriate sections.

However, the mechanism of microwave absorption within a material is more complex. The following equation depicting the skin depth of any conducting material clearly indicates that the absorption is conductivity and permeability dominated, which may be physically explained respectively, in terms of the Ohmic and hysteresis loss suffered by the microwave through leakages while being transmitted through the material thickness respectively.

$$\delta = 1/(\Pi f \mu \sigma)^{1/2} \tag{4}$$

***Table 1:*** EM wave—material interaction analyses.

| Cases | Criteria | Ref. Eqn. | Remarks |
|---|---|---|---|
| $R = -1$ | $\eta_2 = 0$ (material is perfect conductor) | 1 | A perfect conductor is also a perfect reflector of microwaves; note that the negative sign of R indicates that the reflected wave is exactly opposite in direction to the incident wave. |
| $R = 0$ | $\eta_2 = \eta_1 = 377$ Ohms/sq. (material is impedance matched with air) | 1 | An impedance matched material prevents any reflection of microwaves from the interface. |
| $T = 0$ | $\eta_2 = 0$ (material is perfect conductor) | 2 | A perfect conductor is also perfectly opaque to microwaves. |
| $T = 1$ | $\eta_2 = \eta_1 = 377$ Ohms/sq. (material is impedance matched with air) | 2 | An impedance matched material ensures 100% transmission through the interface. |
| $\eta$ | $f(\mu)$<br>$g(\sigma,\varepsilon)$<br>(where f & g are mathematical functions of the parenthised variables) | 3 | The complex impedance of a material is an increasing function (f) of magnetic permeability and a decreasing function (g) of electrical conductivity and the dielectric constant. |
| $\eta = (\mu/\varepsilon)^{1/2}$ | $\sigma << w\varepsilon$ | 3 | The complex impedance term becomes much simplified for non-conductors of electricity. |

where
f = Frequency of the incident wave &
$\delta$ = Depth of penetration or skin depth of the material
≡ Thickness at which incident wave intensity reduces to $e^{-1} = 0.368$ of original.

This phenomenon can be still better explained by the propagation constant equation:

$$\gamma = \alpha + i\beta \tag{5}$$

where
$\gamma$ = Propagation constant,
$\alpha$ = Attenuation constant &
$\beta$ = Phase constant.

Now, the attenuation and the phase constants are defined as:

$$\alpha = \lambda_m w^2 (\varepsilon' \mu'' + (\varepsilon'' \mu')/4\Pi \tag{6}$$

$$\beta = 2\Pi/\lambda_m \tag{7}$$

where
$\lambda_m$ = Wavelength of microwave in the material,
$\varepsilon'$ = Real part of complex permittivity of the material,
$\varepsilon''$ = Imaginary part of complex permittivity of the material,
$\mu'$ = Real part of complex permeability of the material &
$\mu''$ = Imaginary part of complex permeability of the material.

Now, the index of absorption (k) within a material is defined by:

$$k = \alpha/\beta \tag{8}$$

The above equation clearly indicates that for a given incident radiation, the absorption capability of the material increases with the increase of both real and imaginary parts of the dielectric permittivity and the magnetic permeability.

With the above background of fundamental EM theories, the following sections will attempt to analyze various divergent case study applications of composite materials in the aerospace industry.

## 3 EM Wave Transparent Composites

### 3.1 *Application areas*

**Radome:** Physical shield for any antenna or radar, used to protect the same from external environment with minimum possible degradation in antennae characteristics.

The most important application area of microwave transparent composite materials in the aerospace industry is in the field of radomes and antennae covers. Radomes are defined as electromagnetic windows consisting of covers or housings meant to protect an antenna from mechanical damage and other environmental conditions. Naturally, they need to have the necessary structural strength and be designed so as not to deteriorate the electromagnetic performance of the antenna beyond an allowable limit under operational conditions.

### 3.2 *The EM requirements*

Depending on the operational frequencies, the materials used to make these radomes need to be transparent to microwave over either a narrow or a broad band of the EM spectrum. As discussed before, Equation 2 clearly indicates that a necessary condition for perfect transmission across a material (i.e., T = 1) is to ensure an impedance matching of the material with that of free space ($\eta_2 = \eta_1$), which actually eliminates any reflection loss from the surface. However, to reduce the loss of microwave energy through the material, Equation 6 imposes that the dielectric $\varepsilon$ and the magnetic $\mu$ (both real and imaginary part of each) of the material be as low as possible. Since most of the radomes are made of non-magnetic materials, the problem effectively boils down to reducing $\varepsilon'$ and $\varepsilon''$ of these materials, and design them to be as close as possible to those of the free space ($\varepsilon_0 = 1 + j0$). In addition to the dielectric properties, the radome performances are often also sensitive functions of the material thickness and relevant concepts regarding these will be elaborated later. Further, especially for air-borne applications, these radomes also need to provide sufficient structural protection to the in-house antennae and withstand high degrees of aerodynamic loads over a defined temperature band.

### 3.3 *The past*

The evolution of radome material technologies has largely followed the introduction and development of microwave antennae, particularly those meant for airborne applications. Several past literatures amply illustrated the material technologies associated with such radomes, in terms of electromagnetic field theories, dielectric material selection and construction patterns. Historically, a variety of materials have been used for constructing radomes, including balsa and plywood in the early structures. Modern radomes are manufactured using composite materials such as fiberglass, quartz and aramid fibers held together with polyester, epoxy and other resins. Foam and honeycomb cores are often added between inner and outer "skins" of the radome to function as low dielectric constant spacer materials, providing structural strength and rigidity.

In general, these radomes can be broadly classified and discussed with respect of their material selection and construction geometry.

**3.3.1 Classification of radomes as per materials:** As indicated earlier, desirable properties of a radome material include: (i) Low dielectric properties ($\varepsilon'$ and $\tan\delta = \varepsilon''/\varepsilon'$), (ii) Adequate glass transition temperature ($T_g$) depending on the specific application, and (iii) Sufficient thermal & oxidative stability. The last two attributes are essentially important for supersonic and hypersonic platforms and of course for the re-entry type of vehicles, wherein the skin temperatures experienced by the radomes are exceptionally high.

Based on the above requirements, the materials that qualify as candidates for different grades of airborne radomes can be broadly classified as ceramic based and polymer based, as discussed in the following sections:

***3.3.1.1 Polymer based radome materials:*** A brief summary of the polymer based materials (including the reinforcement fibers for composites) are provided in Table 2.

Pure polymer based monolithic thermoplastic radomes were initially used for millimeter wave applications, which were subsequently replaced by advanced thermoplastics owing to superior resistances to rain erosion, moisture absorption and impact loads of the latter (refer Table 2 for details). However, as reflected in the Table 2, it is the thermoset resins that are most commonly used for all types of civilian and defence radomes, mainly owing to their easier processability, improved mechanical properties and significantly lower coefficients of thermal expansion (CTE).

***Table 2:*** Typical dielectric properties of the polymers, reinforcements and composites.

| | In X-band | | |
|---|---|---|---|
| Materials | $\varepsilon'$ | $\tan\delta$ | Remarks (if any) |
| **Thermoplastic polymers** | | | |
| Rexolite | 2.54 | 0.0005 | Early stage monolithic radomes without any reinforcement |
| Nylon | 3.1 | 0.018 | |
| Teflon | 2.1 | 0.0003 | |
| Polystyrene (PS) | 2.6 | 0.0004 | |
| Plexiglass | 2.6 | 0.015 | |
| Polyethylene (PE) | 2.3 | 0.0004 | |
| Poly ether ether ketone (PEEK) | 3.2 | 0.003 | Advanced thermoplastics with improved rain erosion resistance, relatively lower moisture absorption and superior impact properties |
| Poly ether sulphone (PES) | 3.4 | 0.013 | |
| Poly carbonate (PC) | 3.0 | 0.01 | |
| Poly ether imide (PEI) | 3.05 | 0.004 | |
| Poly phenylene oxide (PPO) | 2.8 | 0.002 | |
| **Thermoset polymers** | | | |
| Epoxy | 2.8 | 0.012 | Most widely used matrix materials for civilian and defence aerospace applications, including for the radomes because of their exceptional structural properties at relatively higher temperatures. Epoxies are the most commonly used resins but can withstand up to 150°C only, whereas polyimides and cyanate esters can be serviced even up to 400°C |
| Polyester | 2.7 | 0.005 | |
| Polyimide | 3.2 | 0.005 | |
| Cyanate ester | 3.3 | 0.007 | |
| **Reinforcements** | | | |
| Quartz | 3.8 | 0.0002 | Very high silica content, most attractive radome material, but extremely costly |
| D-glass | 4.0 | 0.0026 | Best radome material among the glass variants, but low in strength and high in cost |
| Aramid (Kevlar$^{TM}$) | 3.8 | 0.01 | Low $\varepsilon$ but a high $\tan\delta$, very attractive for low weight-high strength applications, but has problems with processing (including machining), moisture absorption and cost |
| S-glass | 5.2 | 0.007 | More common variants of glass and not ideally suitable for radome applications |
| E-glass | 6.13 | 0.0039 | |

Further, some of these thermoset matrices can even withstand temperatures to the tune of 350°C–400°C, which is significantly higher than the capabilities offered by most common thermoplastics. Among the thermoset resins, epoxies are the real workhorses for the aerospace industry. However, the relatively higher dipole activity and the presence of hydrogen bonding result in a higher tan $\delta$ among these epoxies. Further, the $\varepsilon'$ as well as tan $\delta$ values of these materials tend to increase further with increase in temperature. But, these problems are mitigated in some of the special classes of polyester resins. But even then, either the epoxies or the polyesters can at best operate at a temperature of 150°C, which is often a major limitation for many applications. This issue is taken care of by some of the more recent thermosets, including polyimides and cyanate esters, which can withstand temperatures close to 400°C.

The Table 2 also lists out some of the most common reinforcements used in structural composites and their respective dielectric properties. It must be appreciated that the final dielectric behaviors of the composite material will be some sorts of weighted averages of the dielectric properties of the matrix resins and the reinforcements. As such, both the polymer and the reinforcement have vital roles to play in determining the overall performance of the radomes built out of their composites. Among the reinforcements shown below, quartz is undoubtedly most suited for high performance radomes owing to their very high silica content, a feature that makes them extremely costly as well. D-glass definitely stands out to be the second best choice, but they too have the problems of low strength and high cost. Aramid (Kevlar$^{\text{TM}}$) fibers have low $\varepsilon'$ but high tan $\delta$ values. They are also plagued with problems of processing, very high moisture absorption and cost. Hence, they are selectively used in radomes for low weight-high strength applications only. E-glass and S-glass are the more common variants of glass fibers, but not ideally suitable for radome applications.

It must be understood that the most common radomes are built from composites designed with one or more of the above mentioned polymers and reinforcements. Further, in many sandwich radome constructions, a lightweight core is also used. The cores are either in the forms of honeycomb (e.g. Nomex$^{\text{TM}}$) or as foams (polyurethane foam, Rohacell$^{\text{TM}}$ foam, styrofoam, syntactic foam etc.). These are extremely low loss lightweight materials with dielectric properties very close to that of free space, and are used in a sandwich design in conjunction with suitable skins to improve the rigidity of the radomes. Different types of such sandwich configurations will be discussed in an appropriate section later.

***3.3.1.2 Ceramic based radome materials:*** Though the ceramic materials are not essentially covered within the scope of this paper, a brief mention about this class of materials, especially for microwave transparent applications is unavoidable for the sake of completeness. The ceramic based materials become indispensable for radome applications demanding temperature withstandability of 400°C and above, as in the cases of most supersonic/hypersonic missiles and spacecrafts. Each of these ceramic materials and their composites has their own pros and cons with respect to their dielectric properties, mechanical strength, thermal properties and fabrication ease. The slip cast fused silica (SCFS), a form of silicon dioxide stands out to be one of the best for high velocity applications (even up to Mach 8) for their favourable combinations of different properties like dielectric constant and loss, cost, CTE etc. The dielectric properties of some commonly used radome grade ceramic materials are listed in the Table 3.

Henceforth in this paper, discussions will be restricted to polymer based radome materials only, and other advanced ceramic materials for extremely high temperature radome applications will not be within the scope of this paper.

**3.3.2 Classification of radomes as per construction geometry:** The very well known plane wave transmission equation for radomes is given by:

***Table 3:*** Typical dielectric properties of ceramics and their composites.

| | In X-band | |
|---|---|---|
| Materials | $\varepsilon'$ | tan $\delta$ |
| Alumina | 9.5 | 0.002 |
| Boron nitride | 4.5 | 0.003 |
| Berylia | 4.2 | 0.005 |
| Borosilicate glass | 4.5 | 0.0008 |
| Cordierite | | |
| Pyroceram | 5.6 | 0.002 |
| Rayceram | 4.8 | 0.002 |
| SCFS (Ceradyne) | 3.4 | 0.004 |
| Silicon nitride | 7.0 | 0.002 |
| Glass/aluminium phosphide | 4.0 | 0.001 |

**Table 4:** Types of radome constructions.

| Description | Sketches |
|---|---|
| | ■ Monolithic layer ▒ Foam/Honeycomb |
| Single layer dielectric: Either electrically very thin (t ≤ λ/10√ε) or near multiples of half wave length in thickness (t ≈ λ/2√ε), where ε is the dielectric constant of the material. |  |
| A-type sandwich: Consisting of two stiffened skins, either very thin (t ≤ λ/20√ε) or near multiples of half wave length in thickness (t ≈ λ/2√ε), spaced with a low loss core (foam or honeycomb) of such thickness, so as to substantially cancel skin reflections. |  |
| B-type sandwich: Outer skins of approriate thickness, so as to match the high ε core (i.e. the skins act as quarter wave transformers). |  |
| C-type sandwich: 2 A-type sandwiches stacked back to back (total 5 layers) to allow residual reflections to be further cancelled. |  |
| Multi layer sandwich: Sandwich constructions with more than 5 layers, with very thin skins and suitable cores, to impart high strength and wide band transmission properties, especially for small incident angles. |  |

$$t = n\lambda/2\ (\varepsilon - \sin^2\theta)^{1/2} \qquad (9)$$

where

t = Radome wall thickness,

n = Any integer,

ε = Dielectric constant of the radome material, and

θ = Angle of incidence.

As before, for the sake of simplification, Equation 9 can be rewritten for normal incidence as below:

$$t = n\lambda/2\ \sqrt{\varepsilon} \qquad (10)$$

The above equation forms the base of the theoretical understanding behind most radome constructions as detailed above in Table 4.

All the above types of constructions have their own pros and cons, and a particular construction needs to be identified for any application based on the optimization of performances in terms of electrical transmission and mechanical requirements. Some typical insertion losses that result in some of the above types of constructions are depicted below.

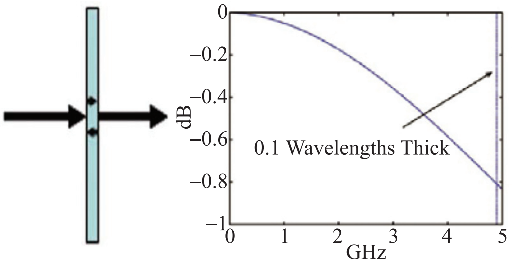


**Figure 3:** Insertion loss for thin wall radome material.

In the Figure 3 above, the insertion loss for an electrically thin (3 mm ≡ 0.1 λ/√ε for 5 GHz) single layer dielectric (ε' = 4 and ε" = 0.01) radome is shown for relatively lower frequency bands (L-band and S-band). The results confirm that the radome performs within allowable limit (generally up to 1 dB loss is acceptable) till 5 GHz, the losses being lower for lower frequencies. For such thin wall constructions, the reflections at the air-dielectric boundary are largely cancelled by the same form the other side of the laminate emanating from the dielectric-air boundary, resulting in very low loss transmission of the incident wave.

Similarly, in a half wavelength radome construction, the round trip of signals (through and reflected) from the laminate interfaces introduce a 360° phase shift, leading to the cancellation of opposing wave fronts, thereby resulting in very

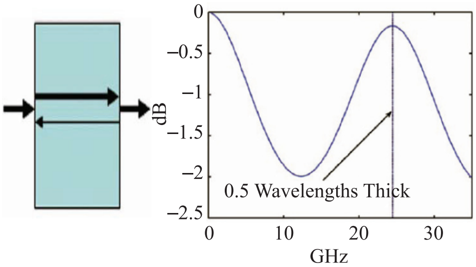


***Figure 4:*** Insertion loss for half wave length radome.

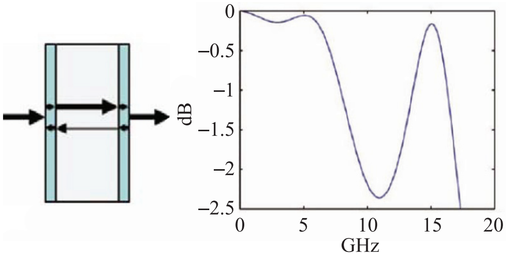


***Figure 5:*** Insertion loss for A-sandwich radome.

high net transmission of incident signals. Figure 4 depicts the same phenomenon.

The figure depicts the reflection loss of the material described in Figure 3 for the same thickness of 3 mm, which is optimized for best transmision at a much higher frequency of 25 GHz.

Similar plot for an A-sandwich (Figure 5) with a low loss foam core (15 mm thick i.e., 0.25λ at 5 GHz) gives best performance at <7 GHz (and at 15 GHz, where the phase shift bcomes an odd multiple of 180°).

In the end, it may be reiterated that the radome constructions actually depend on the specific requirements. A very thin single layer dielectric may be good enough for low frequencies, whereas the half wave length radome concepts may be required for providing sufficient structural stiffness at higher frequency applications. Similarly, the sandwich constructions may be adopted to achieve a superior strength to weight ratio and larger band widths. In addition to the above concepts, some ground based radomes are even made of air pressure supported inflatable materials.

## 3.4 *The present*

Among all possible electromagnetic applications of the polymer matrix composites, microwave transparent applications had been historically more predominant, owing to the fact that most of the glass fiber/resin based conventional composites were by default possessing properties closely akin to those required in such radome or radome type materials. As such, from the composite materials engineering point of view, the technology of this type of material is fairly well established and specific designs need to be optimized for the applications at hand. As such, R&D on this particular electromagnetic application of materials is not the present wave. Nevertheless, the two major associated areas where the research work has been conspicuously focused in the present decade include the following:

**3.4.1 High temperature PMC radomes:** As indicated before, most of the commonly used thermoset resins and their composites can withstand an operational temperature of less than 150°C only. The ceramic radomes, on the other hand, have carved a niche for themselves for conditions of temperatures in excess of 500°C, but at the cost of higher weight and brittleness in the structure. This present scenario leaves a window of opportunity for the polymer composites to fill in the gap between 150°C–500°C, thereby offering lightweight high performance radomes for most supersonic airborne platforms. One of the most recently explored resin systems to bridge this technology gap is the cyanate ester resin systems.[1–21] This new class of thermoset resins cures by cyclotrimerization reaction between three molecules of cyanate monomers to form polycyanurate containing triazine ring. A few properties (thermal and dielectric) of these resins vis-à-vis the other common resin systems as available from the literature are given in the subsequent paragraphs.

Figure 6[16] amply illustrates the superior thermal withstandability of the cyanate ester resins as compared to the commonly available room temperature curable epoxies. The figure shows the thermograms (Storage Modulus & Loss Modulus vs. temperature) of epoxy and cyanate ester resin casts as obtained from Dynamic Mechanical Analysis (DMA) of the respective samples in single cantilever modes. While the former recorded a $T_g$ in excess of 270°C, the latter had the same at as low as about 170°C.

Not just the neat resins, extensive studies have also been conducted to evaluate the properties of the cyanate ester based composites, and to compare them with the conventional epoxy counterparts. Figure 7 presents the dielectric behavior of the epoxy and cyanate ester composites in the form of GFRPs and hollow glass microsphere filled syntactic foams in the X-band.[14] It can be observed that while air provides the baseline, the syntactic foams (both epoxy and CE based almost overlapping) are the nearest to that baseline with dielectric constants of about 1.5. These foams are ideal candidates for core materials in sandwich constructions for broadband transmission, which will be discussed in the next section. The Teflon material, which is known to be excellent in terms of low dielectric constant, have a dielectric constant value of about 2. Among the GFRP variants, the CE based composite showed a slightly lower dielectric constant (4.5) compared to its epoxy counterpart (4.75), both being equivalent in terms of fiber and matrix volume fractions.

However, apart from processing concerns,[16] one major problem that has hindered the widespread application of the cyanate ester resin systems is the anomaly of behavior, especially in the temperature withstandability between the neat resin and its composites. Figure 8 shows the DMA thermograms of a particular grade of cyanate ester resin along with a syntactic foam composite developed using the same resin. While the resin alone recorded a $T_g$ at about 280°C, its composite counterpart had the same at a lower temperature of 185°C.[13] This is not an expected phenomenon, since the temperature withstandability of the composite is mostly controlled by the resin system alone. These observations along with other similar studies raise doubts about whether the properties of the cyanate ester resins do get translated into their composites or not.

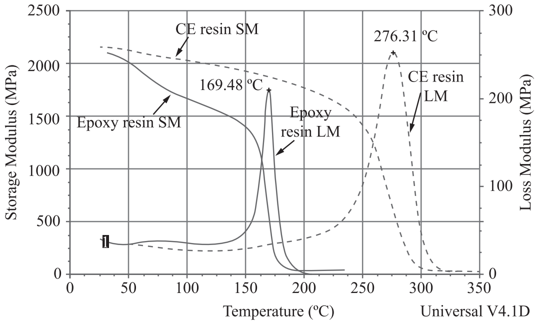


***Figure 6:*** DMA thermograms of CE vis-à-vis epoxy resins.[16]

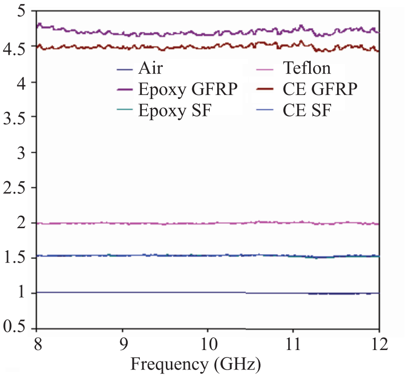


***Figure 7:*** Dielectric constants of epoxy and CE composites in comparison to Teflon and air.[14]

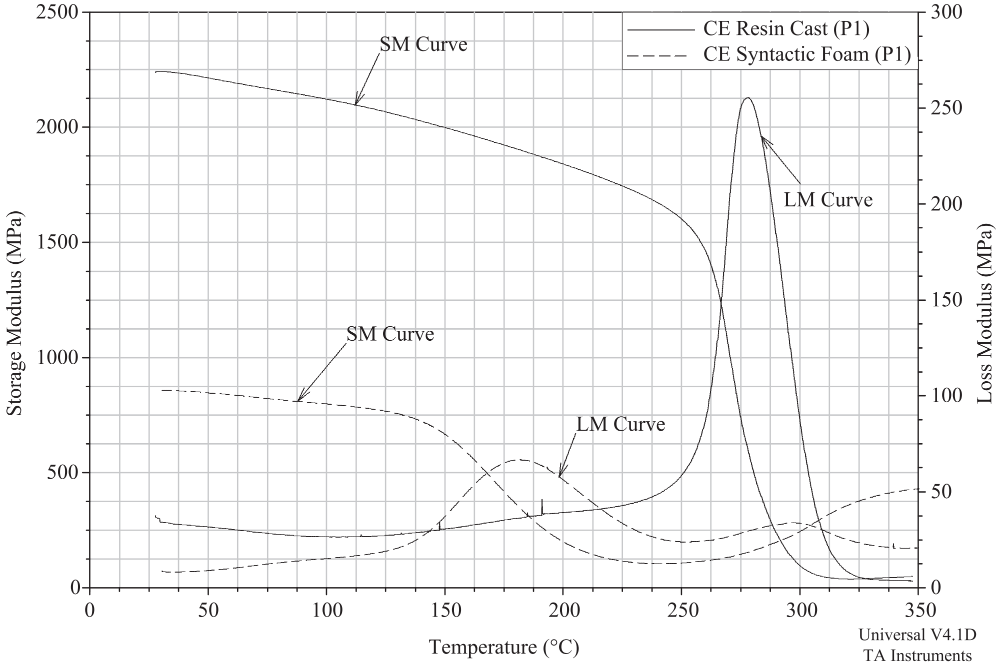


***Figure 8:*** Temperature withstandability of CE resin and CE based syntactic foam.[15]

**3.4.2 Sandwich radomes for broadband applications:** Another area in which research towards microwave transparent composite materials has progressed in the current decade is in the field of broadband sandwich radomes for mostly defence combat aircraft. However, the work being mostly classified, not much direct literature is available on the processes and exact applications adopted in these cases. The most commonly used configurations have been A-sandwich design, with glass or Kevlar fiber reinforced skins and lightweight cores including Rohacell and syntactic foams (both epoxy and cyanate ester resin based).[14]

### 3.5 *The future*

Some of the key areas that are likely to determine the future directions in radome technologies research may include:

**3.5.1 Frequency Selective Surface (FSS) technology for multiple frequency radomes:** In the not so distant future, radomes will be required to be designed for augmenting a lot more stealthiness to the in-built antennae by selectively allowing the passage of one or more predefined frequency signals (uplink and/or downlink), and restrict the transmission of other bands. This can be achieved by employing the so called FSS, as known in the fields of electromagnetics in conjunction with the already known radome materials technologies. FSS however, is more of an electromagnetics technology and not within the direct scope of the material scientists.

**EMI shielding:** Blocking the passage of electromagnetic wave.

**3.5.2 Toughening of high temperature withstandable polymer systems:** As discussed earlier, one of the key hurdles in establishing the CE resin systems as an alternative matrix to develop high temperature withstandable radomes for supersonic applications is its extreme brittleness. In addition to the past endeavors, sufficient future R&D efforts also need to be focused on resolving this issue of toughening the matrix by chemical modification using the blends of epoxies and other thermoplastics or elastomers. Although improving the toughness, such blends will invariably cause reduction in the temperature withstandability of the radomes. The major challenge will be to intelligently optimize the blend chemistries so as to achieve sufficient toughening with minimum compromises in other properties.

**3.5.3 High performance thermoplastics for airborne radome applications:** Some of the advanced high performance thermoplastics like Poly ether ether ketone (PEEK), are known to mitigate most of the common problems that generally plague the thermoplastic family. Though processing these materials still remain a challenge, their improved temperature withstandability, superior microwave transmission and significantly higher mechanical properties make their composites suitable for applications in most radomes. However, further R&D exercises need to be undertaken to establish these materials as able competitors for the thermoset counterparts. Once streamlined, such materials can also benefit from the inherent advantages of thermoplastics like higher toughness and re-processability.

## 4 EM Wave Shielding Composites

### 4.1 *Application areas*

The most promising application area for EM wave shielding composite materials is as the chassis for electronic/avionic enclosures for both ground based and air-borne applications. The default material for such EMI shielding applications had traditionally always been metals and their alloys. The temptation to switch over to the FRPs is primarily borne out of the compulsion to save the chassis weight. In fact, for the same reason, it becomes more justified for airborne enclosures than for the ground based systems, since the gains far outscore the risks in the case of the former.

### 4.2 *The EM requirements*

In optical analogue, an EMI shield is primarily a wall that is totally opaque to the radio or microwaves. Such opacity can be achieved either by the mechanism of reflection or absorption (Figure 2). In other words, the EM criteria for an EM shield basically boils down to $T = 0$, which is achieved under the condition of $\eta_2 = 0$ (from Equation 2), i.e., the material of the shield needs to be highly conductive. This condition not only ensures a very high level of reflection of the EM waves from the surface ($R = -1$ from Equation 1), but also improves the absorption index ($k$) of the material (Equation 6 and Equation 8).

With some basic assumptions associated with such conducting materials, the reflection and absorption characteristics of the shield may actually be further simplified and redefined directly in terms of the material properties as:

$$R_{dB} = 168 + 10 \log \left[(\sigma/\sigma_{Cu}) \cdot (1/\mu_r) \cdot (1/f)\right] \text{ and} \qquad (11)$$

$$A_{dB} = 131.4\, d \left[(\sigma/\sigma_{Cu}) \cdot \mu_r \cdot f\right]^{1/2} \qquad (12)$$

where

$\sigma_{Cu}$ = Volume conductivity of copper ($5.7 \times 10^7$ S/m),

$\mu_r$ = Relative magnetic permeability of the material &

d = Thickness of the shield (m).

Both the above equations reinforce the earlier understanding of the physics of the wave-material interactions, and additionally, they provide us with a scope of numerically estimating the SE of any homogenous material (i.e., $\mu_r$ and $\varepsilon_r$ are constant throughout the thickness d).

## 4.3 *The past*

With increasing weight criticalities in electronic packaging, polymer matrix composites (PMCs) are generating enormous interest as lightweight alternatives to existing metallic electronic enclosures. Virtues like ease of processing, superior specific strength and improved aesthetics of the PMCs have tilted the balance further in their favour. However, the lack of intrinsic conductivity in the traditional PMCs render them unsuitable for such applications because of the extremely critical issue of electromagnetic interference (EMI) associated with such applications. Metals enjoy the inherent advantage of possessing very high electrical conductivity ($\sigma \approx 10^7$ S/m), and hence intrinsic EMI shielding capabilities. However, polymers and their composites in general, are very poor conductors of electricity ($\sigma \approx 10^{-14}$ S/m), which calls for tailoring and tuning these conventional PMCs to meet the specific requirements for electronic packaging applications.

In fact, if the entire gamut of materials is placed in the approximate resistivity scale (Table 5), the family of polymers and ceramics will be at one end ($\rho = 10^{14}$–$10^{18}$ ohm–m), whereas the metals will be at the other ($\rho = 10^{-7}$–$10^{-5}$ ohm–m). The EMI shielding materials lie somewhere in between ($\rho = 10^0$–$10^4$ ohm–m). Hence, historically, the underlying philosophy of designing EMI shielding composite materials had always been to select two or more materials from the above scale such that the combination, on a whole, attained a resistivity in the desired range.

**Table 5:** The approximate resistivity scales.

| Class of materials (–) | Electrical resistivity (Ω-m) |
|---|---|
| Polymers & Ceramics | $10^{14}$–$10^{18}$ |
| Antistatic Materials | $10^{10}$–$10^{13}$ |
| Statically Dissipative Composites | $10^5$–$10^9$ |
| EMI Shielding Composites | $10^0$–$10^4$ |
| Carbon Variants | $10^{-4}$–$10^{-1}$ |
| Metals | $10^{-7}$–$10^{-5}$ |

Stainless steel filled ABS had long been used in power measurement recorders to avoid Electromagnetic Interference/Radio Frequency Interference (EMI/RFI). Metallic silver filled elastomeric gaskets and adhesives for effective EMI shielding as well as environmental sealing applications are also known since long. For critical applications, however, the above mentioned thermoplastic materials suffer from certain limitations because of their inadequate mechanical properties, higher coefficient of thermal expansion (CTE) and shrinkage factors. Hence, for such structures, especially in the fields of aerospace, thermosetting polymers and their reinforced composite versions have become increasingly popular. By the addition of certain conductive fillers in critical quantities (depending upon the percolation threshold of the particular filler in the selected matrix), the conductivity of such thermosetting composites are known to increase to the order of $10^1$ S/m. Other lightweight conductive composites that have been developed and studied use highly conductive graphite ($\sigma = 10^5$ S/m) powders, bromine intercalated graphite ($\sigma = 10^6$ S/m) fibers, nickel coated graphite (NCG) powders, carbon fibers and other special reinforcements/fillers. In addition to these, there are a host of active as well as lapsed patents on similar inventions as well. Once the desired electrical conductivity is achieved, required levels of shielding effectiveness (SE) can also be realized from these composites.

Some instances where such materials were used for practical applications in the aerospace industry in the past include:

a. Composite Optics Inc. COI, USA, under the funding of Office of Naval Research (ONR), had a program to use highly conductive composite materials to provide a more affordable electronic package. A prototype composite chassis based on the existing aluminium design was fabricated and successfully tested to demonstrate its effectiveness in meeting mechanical, thermal and electrical performances (refer google-books on "Affordable, Lightweight, Highly Conductive Polymer Composite Electronic Packaging Structures").
b. Triton Systems Inc. along with NASA Glenn Research Center, USA, have successfully addressed the problem of shielding electronic devices in the space from EMI with lower

weight composite shields as compared to presently used aluminium or tantalum shields (refer http://www.grc.nasa.gov/WWW/epbranch/other/grfabs.htm).

c. Naval Underwater Systems Center, USA had come up with polymeric composite materials for long-term EMI shielding properties by addition of conductive fillers in the form of graphite, Nickel Coated Graphite, Ni-mica and other metallic oxides (refer http://www.dtic.mil/dtic/tr/fulltext/u2/d014847.pdf). The material was designed to meet the requirements of EMI shielding in the light of noisy electronic environment for land and marine applications. In addition to EMI, the composite materials also provided full range of mechanical as well as chemical properties including corrosion resistance and electrochemical compatibility with connecting metallic parts.
d. American Cyanamid Company, USA had developed polymeric composite materials with very high electrical conductivity by incorporating Nickel Coated Graphite powders in the standard resin matrix (refer http://www.google.co.in/patents/US5827997). The resultant composite could be readily used in structural assemblies using established composite manufacturing practices.
e. American Rugged Enclosures Inc., USA are presently offering Graphite composite ATR enclosures (conduction/convection cooled) for both commercial and military applications (refer http://www.areinc.com/pages/content/catalog.html).

However, barring a few exceptions, the activities had mostly concentrated on achieving EMI shielding properties in the polymer composites alone, not really striving to achieve weight efficient structural materials at the same time so that they can be practically put to use in primary or secondary load bearing structures of aircraft. This major consideration was found in most of the more recent R&D on this field, to be discussed in the later sections of this paper.

## 4.4 *The present*

In the present decade, the research works in the field of EMI shielding composites have been guided by three major considerations:

**4.4.1 Advent of novel conductive fillers like carbon nanotubes:** The advent of carbon nanotubes (CNTs) and their improving commercial viability in the present decade has opened up new vistas of research in various fields of science and engineering, the field of electrically conducting and EMI shielding composites not being any exception to that rule. Numerous papers can be cited off late on the effects of CNTs in various grades of polymer matrices on the mechanical and electrical properties of the composites.[22–47]

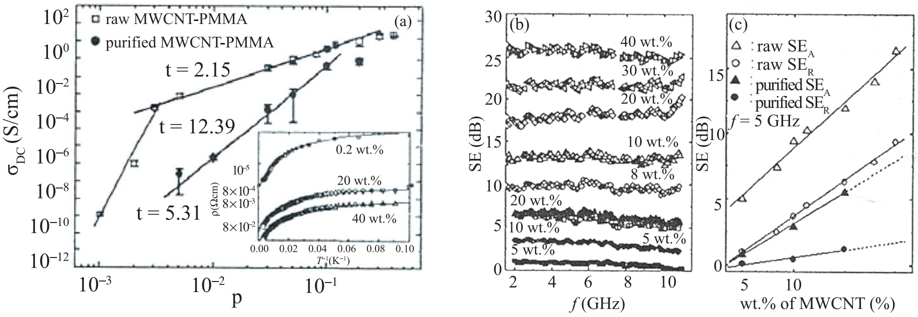
Figure 9 (courtesy Kim et al.) illustrates the effects of as produced and purified multiwall carbon nanotubes (MWCNTs) on the electrical conductivity (Figure 9a shows a clear percolation at about 1 wt.% of MWCNTS) and SE (Figure 9b & c) for MWCNT-PMMA composites.

In fact, Ogasawara et al. even proposed an electrical resistivity model for such CNT composites beyond their percolation threshold.[22] The mathematical model is given by:

$$R_{composite} = R_0/(V_f - V_f^{th}) \quad (13)$$

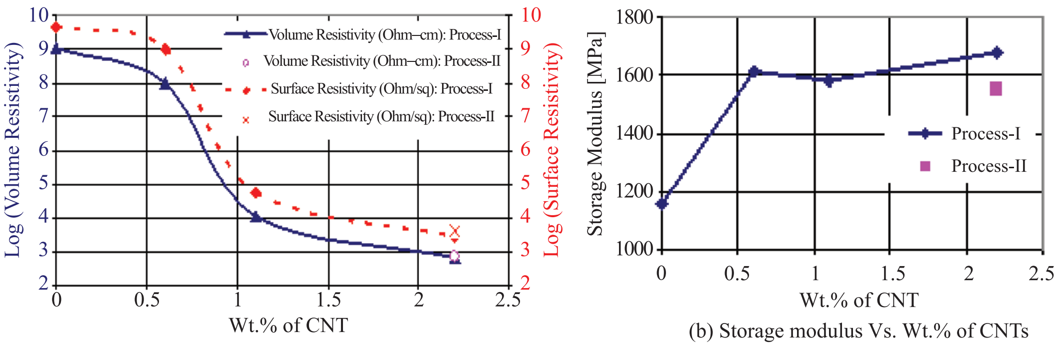
where

$R_{composite}$ = Resistivity of composite
$R_0$ = Resistivity of CNT
$V_f$ = Vol. fraction of CNT
$V_f^{th}$ = Percolation Threshold
#*Valid for $V_f > V_f^{th}$ only (there is no # in the equation)*



(a) DC conductivity Vs. mass fraction (b) SE Vs. frequency (c) SE Vs. wt.% of CNTs

**Figure 9:** Properties of multiwall nanotube-PMMA composites.[24]



(a) Electrical percolation phenomenon

(b) Storage modulus Vs. Wt.% of CNTs

***Figure 10:*** Properties of nanocomposite foams.[27]

As per the above model, the composite resistivity, as expected, decreases with increase in the volume fraction of CNTs loaded. It also amply illustrates that the resistivity of the CNT composites increases with higher resistivity of the CNTs (typically governed by their chiral vectors) and higher percolation threshold. In fact, the most common temptation offered by these CNTs which has triggered most of these studies is the significantly lower percolation threshold (i.e., critical volume fraction of filler above which the electrical resistivity of the composite decreases drastically due to extremely high aspect ratio) offered by them.

The effects of these CNTs on some special class of nanocomposite syntactic foams have also been reported.[27–28] Figure 10(a) shows the typical percolation curve (both volume and surface resistivities) for MWCNT filled syntactic foams manufactured by using two different processes for dispersing the CNTs in the matrix.[27] The MWCNTs used in this study were functionalized with amine terminations to improve the compatibility with and dispersibility within the epoxy matrix. Figure 10(b) shows the corresponding improvements in the ambient temperature Storage Modulus values (measured using DMA in Single Cantilever mode) for the same nanocomposite foams. The improved electrical conductivities of such foams make them ideally suitable for applications as core materials in sandwich constructions designed for EMI shielding applications (courtesy Sankaran et al.).

**4.4.2 Weight efficient structural sandwich designs for airborne applications:** As mentioned earlier, most of the past activities in the field of EMI shielding composites had mostly been concentrated on achieving EMI shielding properties in the polymer composites alone, and not really striving to achieve weight efficient structural materials at the same time, so that they can be put to practical use. In the recent past, however, a few such studies on the use of sandwich material concepts for designing such EMI shielding materials capable of being used as weight efficient load bearing structures have been reported.[29–32] The sandwich design, i.e., lightweight core in between high stiffness skins/face-sheets not only offers superior strength, modulus and rigidity to weight ratio, but also provides ample scope for intelligently incorporating multifunctionalities in the structure by judicious selection of various material design parameters like chemistry of the matrix, nature and thickness of the core and skins, core to sandwich thickness ratio etc. Generally, in most of these studies, various combinations of carbon fabrics along with very fine aluminium and copper meshes have been used as the skins of the sandwiches, whereas insulating as well as electrically conducting syntactic foams have served the purpose of lightweight cores.

Figure 11(a) describes a few such sandwich constructions, whereas Figures 11(b & c) show their SE (1, 10 & 100 MHz) and three point flexural test results respectively.[32] The Matrix A & B mentioned in the Figure 11(a) stands for novolac based (room temperature curable) and DGEBA based (elevated temperature curable) epoxy resins respectively. The results amply illustrate the tailorability of such composite designs in terms of the different material properties by proper selection of matrix, skin and core materials (courtesy Dasgupta et al.).

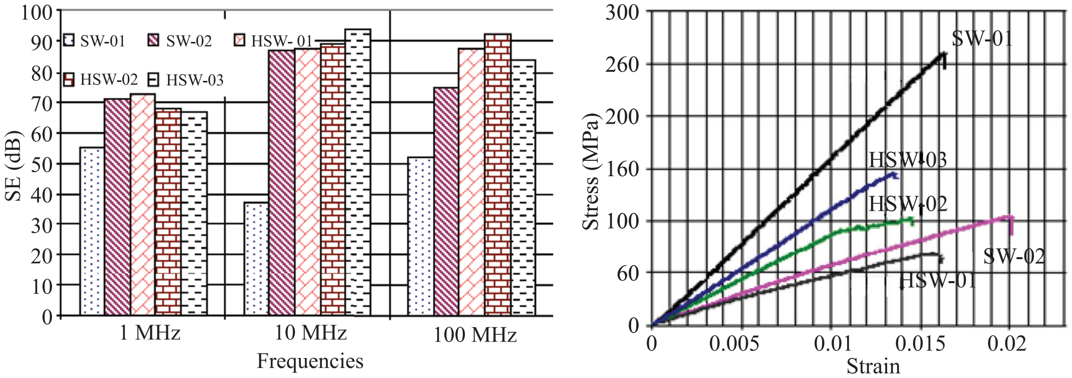
**4.4.3 Theoretical modeling of composite materials for EMI estimations:** Another extremely interesting field that has emerged in the last decade is related to predictive modeling of the shielding efficiencies of these materials. As discussed earlier, the overall electromagnetic shielding provided by any material configuration can be attributed to

| ID | Matrix | Skin | Core | t | d* |
|---|---|---|---|---|---|
| | | | | mm | g/cc |
| SW-01 | Matrix A | Carbon | Insulating Syntactic Foam | 2.75 | 0.76 |
| SW-02 | Matrix A | Al. Mesh-Glass | Insulating Syntactic Foam | 2.75 | 0.81 |
| HSW-01 | Matrix B | Al. Mesh-Glass | Insulating Syntactic Foam | 2.60 | 0.71 |
| HSW-02 | Matrix B | Cu. Mesh-Carbon | Insulating Syntactic Foam | 2.62 | 0.70 |
| HSW-03 | Matrix B | Cu. Mesh-Carbon | Conducting Syntactic Foam | 2.20 | 0.81 |

t = thickness d = density

* Effective density calculated from the mass of sandwich sample

(a) Description of EMI shielding sandwich composites



(b) SE Vs. Frequencies

(c) Flexural Curves

***Figure 11:*** Properties of EMI shielding sandwich materials.[32]

mainly two different mechanisms, viz. reflection at the interface and absorption along the thickness (assuming attenuation & scattering caused by multiple internal reflections to be negligible). Bushko et al.[33] derived an expression based on the theory earlier developed by White[34] for solid planar homogeneous metals for estimating their shielding efficiency which has been shown in Equations 11 and Equation 12. Shown below is the equation derived simply by the addition of the terms in these two equations:

$$\begin{aligned} SE_{dB} &= R_{dB} + A_{dB} \\ &= 168 + 10 \log [(\sigma/\sigma_{Cu}) \cdot (1/\mu_r) \cdot (1/f)] \\ &\quad + 131.4\, d\, [(\sigma/\sigma_{Cu}) \cdot \mu_r \cdot f]^{1/2} \end{aligned} \qquad (14)$$

Krueger[35] and Dasgupta[36] found that the above predictive theory works well for nearly isotropic and homogenous materials with electrical resistivity of 100 ohm-cm or lower, like the electrically conducting foams described above. Figure 12 shows the comparison of predicted and the actual SE values of a chopped carbon

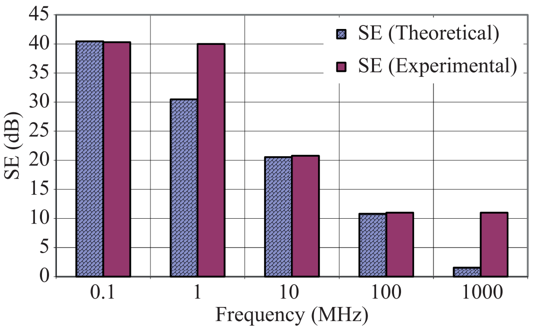


***Figure 12:*** Estimated & measured SE of electrically conducting syntactic foam.[36]

fiber filled electrically conducting syntactic foam, which proves effectivity of the above model as a predictive tool for such estimation (courtesy Dasgupta et al.).

But any such simplified model is not useful in terms of predictive EMI modeling for complex and multilayered anisotropic composite materials. Extensive studies in the fields of computational EM have been recently reported towards attempting to model such complex dielectric materials.[37–39] The complexities in such approaches involve not only the inherent through thickness heterogeneity of such multilayered composites, but also the contributions arising out of the nature and orientations of the subsequent plies and their thicknesses, the diameter and density of the fibers constituting the plies etc. All these micro details need to be incorporated in such multilayered models for EMI shielding prediction in such complex composite materials.

### 4.5 *The future*

Further to the continuation of the above efforts, some dominant feature of research in the area of EMI shielding materials and structures in the immediate future is likely to include:

**4.5.1 Improving the dispersion characteristics of CNTs:** The CNT composites till date, fall far short of theoretical estimates in terms of electrical and mechanical properties. One of the primary reasons attributed to this is the issues related to the dispersion of these nanotubes in the polymer systems. The extremely high surface energy of these CNTs causes them to spontaneously agglomerate, and if these agglomerates are not opened and sufficiently wetted by the matrix resin, a major percent of the CNT fillers are unable to participate in either the load path or the percolation path of the composites. In the years to come, the activities in the fields of practical applications of these nanocomposites are expected to be dominated by the necessities to improve these dispersion characteristics, either through physical mixing (ultra sonication, high speed shear homogenization etc.) or through chemical modifications (i.e. functionalization).

**4.5.2 Modeling the EMI shielding behavior of composites:** In continuation of the present approach, future R&D in this field is also likely to be focused in the solving of problems related to the predictive EMI modeling and simulation for complex, heterogeneous and multilayered composites. This will require enormous simulation skills as well as fabrication of the hardware for eventual validation of the models.

**4.5.3 Thermal management issues:** Apart from EMI shielding issues, another major factor that often threatens to sideline these composites for electronic enclosure applications (especially for densely packed enclosures) is the suspect thermal management of the systems. In order to mitigate this problem, it is expected that the existing materials technology will need to be modified, with the introduction of special components like pitch based high thermal conductivity carbon fibers and aligned carbon nanotubes. These will require extensive studies both in the levels of materials as well as entire system in the near future.

## 5 EM Wave Absorbing Composites

### 5.1 *Application areas*

The major application area for microwave absorbing structural composites is in the design of stealth aircraft structures. Low observability or stealth in aircraft designs refer to the host of technologies, which ensure that the enemy detection mechanisms remain "in the dark" about any aerial invasion into strategic territories. While camouflaging concepts address a part of this issue by providing a visual stealth, the threats from radar detection or IR homing are considered to be much more critical. Though IR homing is extremely effective in shorter ranges and very useful for surface to air missiles (SAM), radar continues to be most enabling for long range detection and tracking. Consequently, Radar Absorbing Structures (RAS) are assuming increasingly significant strategic importance, especially in defence aerospace applications for both manned & unmanned aerial platforms, and has undoubtedly stood out to be one of the most important technologies for realizing stealth design.

**Low observability or stealth in aircraft:** Combination of technologies employed in some military aircraft to reduce its radar, infra red, acoustic and visual signatures.

## 5.2 *The EM requirements*

As indicated above, microwave absorbing materials can be used as EMI shields as well since the basic mechanism of shielding comprises of reflection and/or absorption. However, it is far easier to design and achieve lightweight EMI shielding materials by predominantly exploiting the mechanism of reflection, rather than by that of absorption. Further, higher reflection always demands a higher electrical conductivity in the materials (from Equation 1), which invariably ensures high attenuation within the material as well (from Equation 4). But the challenge begins when the applications demand a very high absorption of EM waves through the material thickness coupled with lowest possible reflection from the surface. Such is the classical problem of stealth materials, also known as Radar Absorbing Materials (RAMs). The target becomes relatively simplified if the RAMs are to be designed for a spot frequency/narrow band of incident EM wave. Such materials can be easily designed for resonance absorption at $\lambda/4$ thicknesses, and have been explained at length in the next section. However, the problem becomes trickier in case of broadband RAM designs. Other than a few multilayered resonant RAM approaches (which have their own limitations as described later), most broadband RAMS are mostly designed taking material level absorptions (dielectric & or/magnetic) into account.

**Radar Cross Section (RCS):** An important figure of merit to ascertain the visibility of any object through a radar; function of size, shape, materials etc.

Now, for the reflection pattern of the EM wave from the material to be controlled to minimum, the reflection from any surface within the material thickness needs to be nominal. This requires that each layer within the design need to be nearly impedance matched (to achieve $R \approx 0$, please refer Equation 1) with the preceding as well as the succeeding layers (i.e., $\eta_{i-1} = \eta_i = \eta_{i+1}$). However, Equation 12 demonstrates that absorption capability of material increases with the increase in both conductivity and permeability of the material. But, any changes in these material parameters will affect the complex impedance (which is required to be controlled) as well (please refer Equation 3). Hence, in order to keep each layer nearly impedance matched with its neighbors, and also improve the absorption characteristics simultaneously, the only plausible approach is to ensure a controlled and incremental increase in the relevant material properties through the thickness of the material, in order to avoid any significant impedance mismatch at any given location within the thickness of the structure. Herein comes the concept of using functionally graded materials (FGM) (dielectric/magnetic) for the same purpose.

## 5.3 *The past*

An aircraft may be designed to be low observable through radar by a combination of different technologies including structures (i.e. through shaping & configurations), materials (i.e. through microwave absorption), electronic warfare (i.e. through electronic jamming) and a few others like plasma etc. Radar detection is a predominant function of the radar cross section (RCS) of the aircraft, which may be defined as the cross-sectional area of a hypothetical perfect spherical reflector offering the same radar signature (reflection pattern) as the aircraft as a whole. Table 6 enlists some typical targets and their X-band (8–12 GHz) RCS values.

While we must understand that all the technologies mentioned above play their roles in reducing the aircraft RCS, in this particular section, we will restrict our discussions to the topics of relevant materials only, viz. RAMs which are essentially materials or coatings whose electrical and magnetic properties have been altered to allow absorption of microwave energy at discrete or broadband frequencies.

Despite the recent upsurge in the interest in RAMs, the technology quest is hardly new. Initial work on producing practical microwave absorbers dates back even before the 2nd World War, with countries like USA, Germany and Britain being the major players. Historically, RAMs had always been broadly classified into two different categories:

**5.3.1 Resonant absorbers:** These materials work on the principle of controlling the phase/path difference of the incident and the reflected waves, by tailoring the material thickness to integral multiples of $\lambda/4$ (ideally $\lambda/4\sqrt{\varepsilon}$; but since most of the time the $\varepsilon$ of the material is chosen to be as close to 1 as possible, these are better known as $\lambda/4$ or quarter wave length absorbers). Although predominantly designed for a spot frequency,

***Table 6:*** Typical RCS values.

| Target | RCS ($m^2$) |
|---|---|
| Large commercial airplane | 100 |
| B-52 bomber | 40–100 |
| Large fighter aircraft | 5–6 |
| Small fighter aircraft | 2–3 |
| Human being | 1 |
| F-117 fighter aircraft | 0.1 |
| B-2 stealth bomber | 0.01 |
| Small bird | 0.01 |
| Bug/insect | 0.00001 |

these materials may still be intelligently tuned to give a significant broadband absorption.

An earliest known example of such resonant absorbers was the Salisbury Screen wherein, a space cloth, i.e., a resistive sheet with a surface resistivity of 377 ohms per square (free space impedance) was placed one-quarter wavelength from the metal surface to be shielded. 25–30 dB absorption was obtained from such absorbers in the quarter-wave frequency. The first patented Salisbury Screen consisted of a front face of graphite-coated canvas, a wood spacer providing the quarter-wave distance with an aluminum foil backing. Modern Salisbury Screens generally use a graphite-impregnated fiberglass face sheet, a lightweight foam spacer and a conductive backing. Another similar patented material, known as the Halpern Anti-Radiation Paint (HARP) Cloth was produced in USA by aligning conductive flakes of aluminum, copper or ferromagnetic materials in a non-conductive binder, such as rubber or plastics. Dielectric constants obtained by these methods were in the order of 50, and could reduce the quarter-wave thickness of the absorber by a factor of 5–10 (please recall that $d = \lambda/4\sqrt{\varepsilon}$). Another approach to such resonant absorbers was through the addition of magnetic fillers like ferrites and carbonyl iron to produce a range of absorbers operating from 1–18 GHz. When bonded to the metal superstructure, these materials were found to reduce reflections by 20–30 dB.

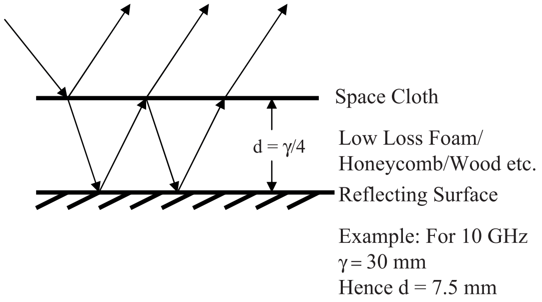
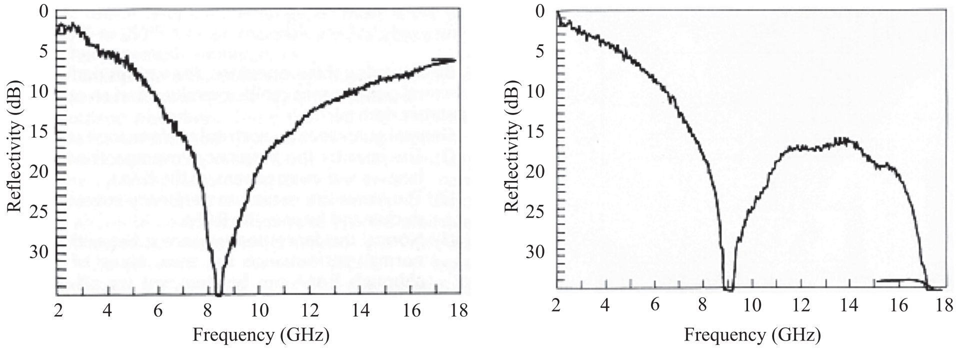


**Figure 13:** Typical resonant absorber.

Figure 13 illustrates the operation of such Salisbury Screen absorbers. A wave incident upon the surface of the screen is partially reflected and partially transmitted. The transmitted portion undergoes multiple internal reflections to give rise to a series of emergent waves. At the design frequency, the sum of the emergent waves is equal in amplitude but 180° out of phase with, the initial reflected portion. While in theory, zero reflection takes place at this frequency; in practice, absorption of greater than 30dB (99.9 percent) may be well be actually achieved from such absorbers (Refer Figure 14a).

The inherent problems of the Salisbury Screen are its narrow band limitations and very high thickness, especially at lower frequencies. As in the case of HARP Cloth, the thickness, however, can be substantially reduced by increasing the μ and ε of the intermediate core. Multilayered resonant absorbers, better known as Jaumann Absorbers can also be tuned for dual/multiple frequencies, thereby making them suitable for broadband applications (Figure 14b). However, thickness remains a major cause of concern and hindrance to the practical applications of these Jaumann absorbers in aerospace.

**5.3.2 Graded index (GI) absorbers:** The principle of operation in GI absorbers is entirely different from that of the resonant type. If we recall earlier discussions, the EM requirement of a RAM is to minimize reflection but simultaneously maximize absorption of EM wave. These apparently contradictory requirements can be achieved only by the concepts of FGM wherein absorption may be achieved by a gradual tapering of impedance along the material thickness from that of free



(a) Salisbury Screen (8.5 GHz)

(b) Dual Band Jaumann Absorber (8.5 & 17 GHz)

**Figure 14:** Typical return loss plots of resonant absorbers.

space at the incidence plane to a highly lossy state near the reflecting plane. If this transition is done smoothly, reflection from any layer within the material can be minimized. Some examples of such materials include Dallan Bach absorber and Jacob's absorber. In general, such GI absorbers can be broadly classified into two categories:

***5.3.2.1 Dielectric GI absorbers:*** These materials depend on the ohmic loss of energy that can be achieved by loading lossy fillers like carbon black, graphite, carbon nanotubes, conducting polymers etc. in polymer matrices. The classical example of this concept can be seen in the absorbing pyramids inside any anechoic chamber, where the absorbing medium is a conductive carbon in a polyurethane foam. Though absorption levels of greater than 50 dB can be obtained with such very thick pyramids, these are however, impractical for RCS reduction in aerospace structures. However, good levels of reflectivity reduction (greater than 20 dB) can be achieved in materials even less than one-third wavelength thick by ensuring a gradual transition of dielectric properties by using a conductive carbon-plastic coating (Figure 15). This method of gradual impedance transition can also be applied to other materials.

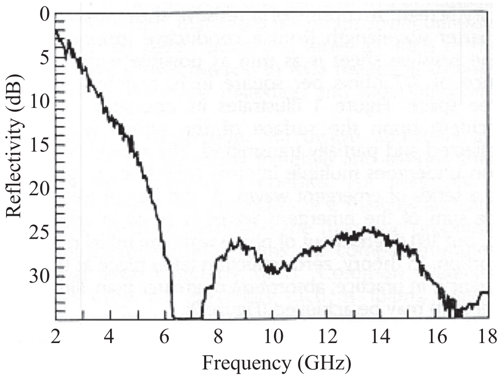


***Figure 15:*** Typical return loss plot of a broadband graded index absorber.

***5.3.2.2 Magnetic GI absorbers:*** The concepts of these are exactly similar to that of the dielectric type of GI absorbers, except the fact that these materials depend on the magnetic hysteresis effects, and subsequent losses within the material. Such composites can be obtained when particles like ferrites, magnetites and carbonyl iron are filled in polymer matrices.

Table 7 presents a quick comparison of the above types of RAMs.

## 5.4 *The present*

It may be noted that the topic of stealth technologies in general and stealth materials in particular is strictly classified and very few open literature can be traced on the subject.[48–60] Some trends of the continuing R&D exercises in the field of RAMs based on the limited available resources can be thus summarized:

**5.4.1 Carbon nanotube—polyaniline based RAM:** Defence R&D Canada-Atlantic are exploring the capabilities of conducting polymer (polyaniline) coated CNTs for potential RAMs.[48] Polyaniline are expected to be strong micro and millimetre wave absorbers because of their high conductivity at those frequencies, whereas CNTs, with their high intrinsic conductivity and chirality, are believed to possess both absorbing and shielding capabilities. As a result, the composites designed out of them have manifested improved microwave absorption in X-band and subsequent dissipation of the heat. The intrinsic microwave absorbing capabilities of CNTs have also been reported by Kim et al.[49]

**5.4.2 Magnetic superconductors & ferroxide based nanocomposites for microwave applications:** NATO Reintegration Grant Project

***Table 7:*** Comparison of different known types of RAMs.

| RAM types | | Advantages | Disadvantages | Other remarks |
|---|---|---|---|---|
| Resonant RAM | | 1. Simplest material design<br>2. Very high Return Loss achievable | 1. Too thick at lower frequencies<br>2. Generally narrow band | 1. Broadband loss may be improved for multiple layer designs<br>2. Thickness can be reduced by tuning the core properties |
| GI RAM | Dielectric | Significant scope after advent of special fillers like fullerenes and CNTs | 1. Uniform dispersion of fillers in the matrix is challenging<br>2. Complex designs (mostly FGM) requiring extensive modeling | Functionalizing the CNTs may improve their dispersibility |
| | Magnetic | 1. Very high loss at RF frequencies<br>2. Popular for naval platforms | 1. Very thick, heavy & brittle<br>2. Permeability reduces drastically at higher frequencies | Specially developed high frequency ferrites/nano ferrites may solve the problems |

(RIG 981472) focuses on the synthesis routes for nanoscale magnetite, which are emerging as extremely promising material for not only microwave absorbers, but also for variety of applications including high capacity magnetic storage media, element of nanoscale ICs etc.[50]

**5.4.3 Ferrite nanoparticles in polymer composites:** Swedish Defence Research Agency is focusing its research on the synthesis of ferrite nanoparticles with a range of compositions and integration of these into acrylic matrix.[51] They are also concentrating on functionalization of these ferrite particle surfaces for better compatibility with the polymer matrix. The overall objective of this endeavor is to combine the functions of microwave/radar absorption with reasonable degree of mechanical load bearing capacity.

**5.4.4 Magnetic & dielectric based RAM and their RCS evaluation:** MC Rezende et al. reported the development of rubber based magnetic (magnetite & ferrite) and dielectric (polyaniline) RAMs (in form of 4 mm thick panels) and their X-Band RCS evaluation by double face panel method.[52]

**5.4.5 Resonant absorber sandwich RAM:** Park et al. reported developing radar absorbing sandwich structures by incorporation of carbon black in the face sheets and CNTs in the polyurethane foam cores.[53] They theoretically estimated the Return Loss for three different material compositions and validated them with experimental measurements. More than 10 dB loss was obtained for all the material designs at X-Band.

**5.4.6 Ferrite composite coatings:** IIT-Roorkee, India developed electroless coating techniques for Ni-P-nano/sub micron ferrite composites for microwave applications.[54] Ba-Zn-Co based ferrite particles were synthesized and the composite coatings characterized for microwave absorption in 12–18 GHz band, and absorption up to 20 dB reported, depending upon the volume fraction of ferrite in the matrix. However, the up-scalability of the technology for engineering applications remains to be addressed.

**5.4.7 Circuit analog RAM:** Theoretical design of RAMs and space cloth of various specifications through circuit analogue approach[55] have also been reported relatively recently.

**5.4.8 Nano-composite RAM:** Composite design and fabrication, including nanocomposites for RAM and related applications[56] have also been reported in recent past.

## 5.5 *The future*

Further to the continuation of the above efforts, some dominant feature of research in the area of RAM in the years to come is likely to include:

**5.5.1 Coupling EM energy absorption and scattering within the material design:** In some materials or structures, internal geometry can be designed in such a way that the structure as a whole possesses a low RCS, with no change in the outer surface/contour. Strictly speaking, though these structures should not be regarded as RAMs per se, but they are grouped along with the other RAMs because they essentially serve the same purpose of RCS reduction.

**5.5.2 Enabling technologies for manufacturing of radar absorbing structures (RAS):** Most of the above described RAM concepts require a technology that will enable the material scientists to realize a composite layer of custom defined electrical/magnetic properties. This is presently achieved either by a circuit analogue approach (in which an electrical circuit/pattern of known equivalent resistance is printed on a resistive sheet) or by a composite material approach (loading critical recipes of fillers like graphite or carbon nanotubes on FRP sheet). However, both the approaches presently suffer from different limitations in terms of precision, reliability, repeatability of properties, manufacturability etc. and extensive R&D on such manufacturing technologies is indispensable for practical and usable RAMs and RAS of future.

**5.5.3 Hybrid RAMs:** A closer look at the Equation 3 tells us that $\mu$ and $\varepsilon$ have opposite effects on the overall $\eta$ of the medium, which offers an opportunity, wherein both $\mu$ and $\varepsilon$ of subsequent layers in a GI RAM may be gradually increased, so as to ensure that the resultant $\eta$ of each layer remains almost same throughout the material thickness, but the absorption capability within the material continues to get augmented through each layer. This is the concept of a hybrid RAM (both dielectric and magnetic) that offers to provide the benefits of both the worlds to the material designers. Extensive works are envisaged in near future on such hybrid RAM concepts.

**5.5.4 Other approaches:** Other than the advances in materials technology alone, few other futuristic endeavors that may have a positive impact in development of improved RAMs include those in the fields of plasma synthesis, Frequency Selective Surfaces (FSS) etc.

## 6 Summary

Polymer composites for electromagnetic requirements are a relatively new and emerging field, primarily propelled by the aerospace industry because of its extreme weight criticality. The field is vastly interdisciplinary, demanding extensive understanding of materials technology, basic electromagnetics and system design compulsions. Materials interact with EM waves through one or more of the three mechanisms, viz. transmission, reflection and absorption, each of which respectively plays a dominant role in the most typical electromagnetic applications in aerospace structures, viz., radomes, EMI shields and RAMs/RAS. The paper has attempted to explain each of these phenomena and applications, with a brief background of fundamental electromagnetics and glimpses of past, present and future states of the art. Besides, other related issues like static discharge, lightning protection, electrical grounding, galvanic corrosion etc., are also gaining prominence within composite applications in aircraft structures, but have not been discussed in this paper.

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