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ANECHOIC CHAMBER EVALUATION

by

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Introduction

The Boeing Engineering and Construction Engineers, Inc., is principal contractor for the construction of a shielded anechoic chamber for the Ford Motor Company at its proving grounds in Romeo, Michigan. The chamber is designed for EMI measurements with unusually stringent performance requirements particularly at low frequencies (down to 20 MHz). The chamber is partly constructed, but because of problems that have arisen, it has become necessary to re-assess the design of several features of the chamber, not least the absorbing material to be used.

The Radiation Laboratory was made aware of some of these problems during extensive discussions with representatives of the Ford Motor Co. in late 1980 and early 1981. In November 1981 we were asked by BE&CE to provide technical assistance with the chamber design, and on 24 November Mr. J. E. Ferris of this laboratory visited BE&CE to discuss their work. The following material has been prepared in response to specific questions that were asked at that time.

Chamber Design

Ray tracing guided by experience is the only feasible method of anechoic chamber design and has proved to be effective in practice. In the present case, however, the low frequency coverage required is beyond that which we have any familiarity with, and is pressing the state of the art. At higher frequencies it is generally possible to overdesign, so that the quiet zone specification is achieved even if the absorber does not quite attain its rating, or if there are secondary (or subsidiary) ray paths which were not included in the design. Without doubt, 20 (or even) 50 MHz is pushing ray tracing to its limits, and a major question is the extent to which a pyramidal absorber acts as a planar reflector at these frequencies. We believe that is does so to a reasonable degree, but if in practice the specular lobe has fallen off by only (say) 5 dB at 10 degrees on either side of the specular direction, this would affect the design of the "valley" areas to achieve the quiet zone specification at the lowest frequencies. This is not unlikely, particularly since a linear dimension of a valley side is less than a wavelength at 50 MHz and below. It is also questionable whether the so-called fence will be effective at the lower frequencies where the wavelength is much larger than the dimensions. Note that these criticisms still apply if the absorber does scatter only specularly: see, for example, the "specular" lobe width of a metallic strip of dimension comparable to a wavelength.

Recommendation

To test the specularity of reflection from pyramidal absorbers at the lower frequencies, use the arch set-up at the lowest possible frequency (1 GHz?) to measure reflection from "serrated" material having 3 inch pyramids approximately, thereby roughly simulating 12 foot pyramids at 20 MHz. Illuminate at (say) 20 degrees from normal and measure the reflected signal as a function of angle about the direction of specular reflection.

Pyramidal Absorbers

The pyramidal absorber is a standard type produced by most absorber manufacturers for static applications such as anechoic chamber construction. The pyramidal structures may have lengths up to 12 feet (the largest generally available), with square base 2 feet on a side. The lower the frequency at which the absorber must be effective, the larger the size.

The pyramids are made of an expanded foam material which is loaded, typically with carbon particles, in the expansion process. With adequate manufacturing control, the loading is uniform, so that the effective relative permittivity or dielectric constant can be obtained from a knowledge of the permittivities of the expanded foam and the particles and the loading, expressed (for example) as a percent weight.

For an absorber to be effective over a broad frequency range, two criteria must be met: (i) the surface impedance must match that of free space so that the field will penetrate with minimal (ideally zero) reflection from the surface; and (ii) all energy that enters must be absorbed before it can return to the surface after reflection at the metal wall that typically backs the absorber. The purpose of the pyramidal shape is to provide the match over a range of frequencies and angles, and since the loading of the material is uniform, the shaping is the sole mechanism by which the surface reflection is minimized. Obviously, the purpose of the loading is to absorb the energy that penetrates, since the unloaded foam is virtually lossless.

The foam is typically polyurethane, and over a wide range of frequencies a reasonable approximation to its relative permittivity is

$$\frac{\varepsilon}{\varepsilon_o} = 1 + \frac{\rho}{40} \quad , \tag{1}$$

(Radiation Laboratory Report 388289-1-F) where ρ is the density (lbs/ft^3) and the factor 1/40 is derived from a knowledge of the permittivity vs density of the base material (urea). Thus, for $\rho = 2.8$

$$\frac{\varepsilon}{\varepsilon_o} = 1.07 \quad ,$$

and since the permittivity of urea varies little over frequency, e.g.,

	10 MHz	100 MHz	300 MHz
$\varepsilon'/\varepsilon_o$	5.7	5.2	5.1
$\tan\delta \times 10^4$	410	500	530

(Von Hippel, 1954), it is not unreasonable to assume that the permittivity of polyurethane foam is real (lossless) and independent of frequency over the more critical low frequency range at least. If the foam is now loaded with carbon particles, the relative permittivity of the resulting material is

$$\frac{\varepsilon}{\varepsilon_o} = 1.07\ (1 - \gamma) + \gamma\,\frac{\varepsilon_c}{\varepsilon_o} \quad , \tag{2}$$

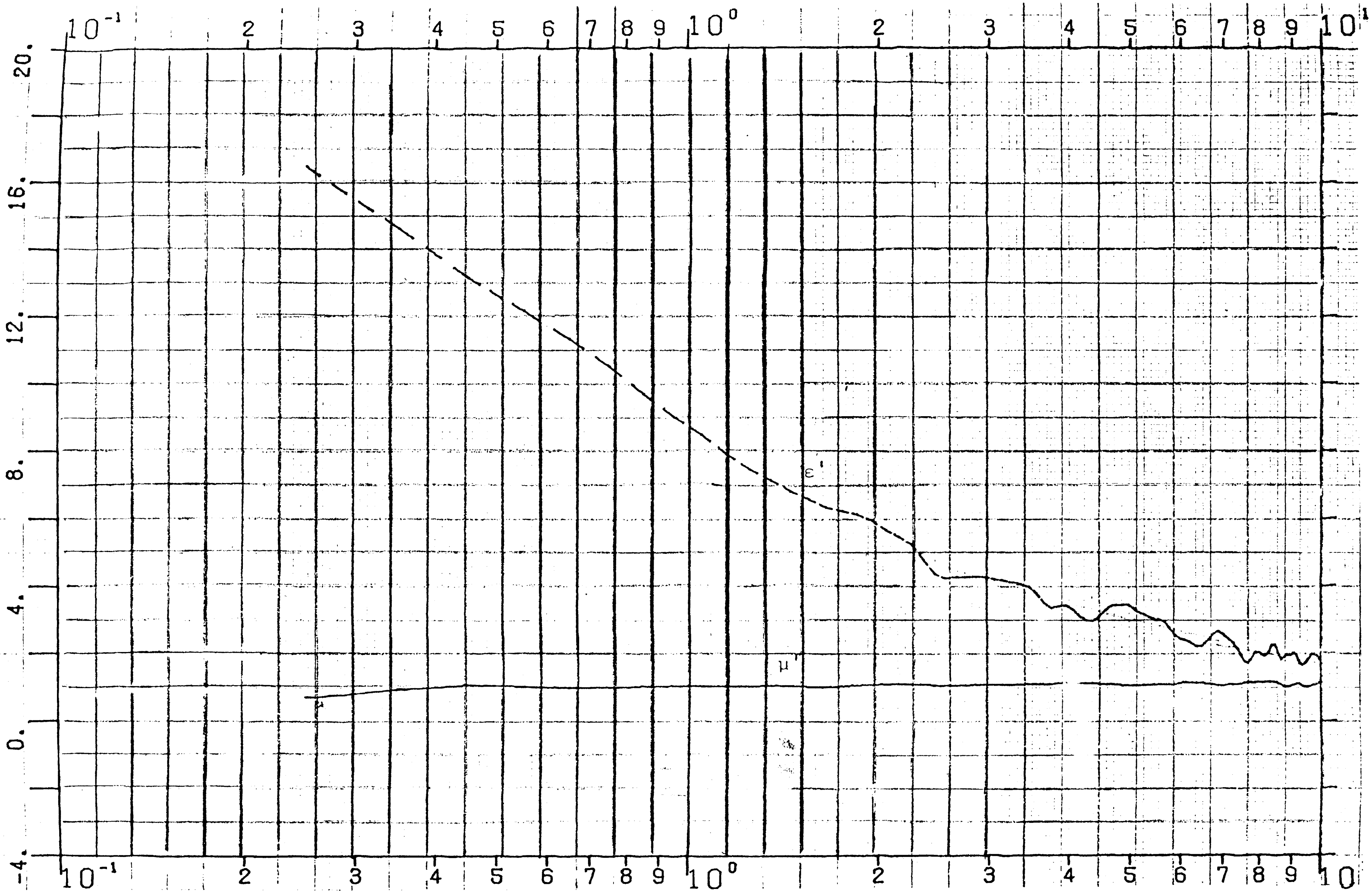
where $\varepsilon_c = \varepsilon_c' + i\varepsilon_c''$ is the permittivity of carbon and γ $(0 \leq \gamma \leq 1)$ is the fractional loading by volume. We can convert γ to the more common fractional loading by weight, γ_w, knowing the densities ρ and ρ_c of the expanded foam and carbon respectively using

$$\gamma_w = \gamma\rho_c/\rho \quad , \tag{3}$$

and loadings in the range $0.05 \leq \gamma_w \leq 0.10$ are typical of pyramidal material.

Unfortunately, the appropriate values of ε_c' and $\varepsilon_c''(= \varepsilon_c' \tan \delta_c)$ and their frequency dependence are not known, but there is evidence to suggest that both increase with decreasing frequency when the frequency is sufficiently low. Figures 1 and 2 show ε' and ε'' for LS-26 material measured by the Avionics Laboratory of Wright-Patterson Air Force Base as a function of frequency using a time domain reflectometer. The permeability μ' and μ'' are also shown and confirm that the material is, indeed, non-magnetic. The LS-26 material is a flat surface carbon-loaded foam whose loading is much heavier than would be the case for a pyramidal absorber, and this could be the reason for the pronounced frequency variation which is evident even above 1 GHz. On the other hand, $\tan \delta (= \varepsilon''/\varepsilon')$ is contributed entirely by the loading, and Figs. 1 through 2 indicate that $\tan \delta$ varies only between 1.3 and 1.6 over the range $0.3 \leq f \leq 5$ GHz.

If ε_c were unknown, it would be relatively easy to computer-model the performance of a pyramidal material, and this would show



LS-26 #2(270MILS) 28APR77 273/JK

FREQUENCY (GHz)

Fig. 1: Measured ε' and μ' of LS-26 material (Radiation Laboratory report 014449-1-F)

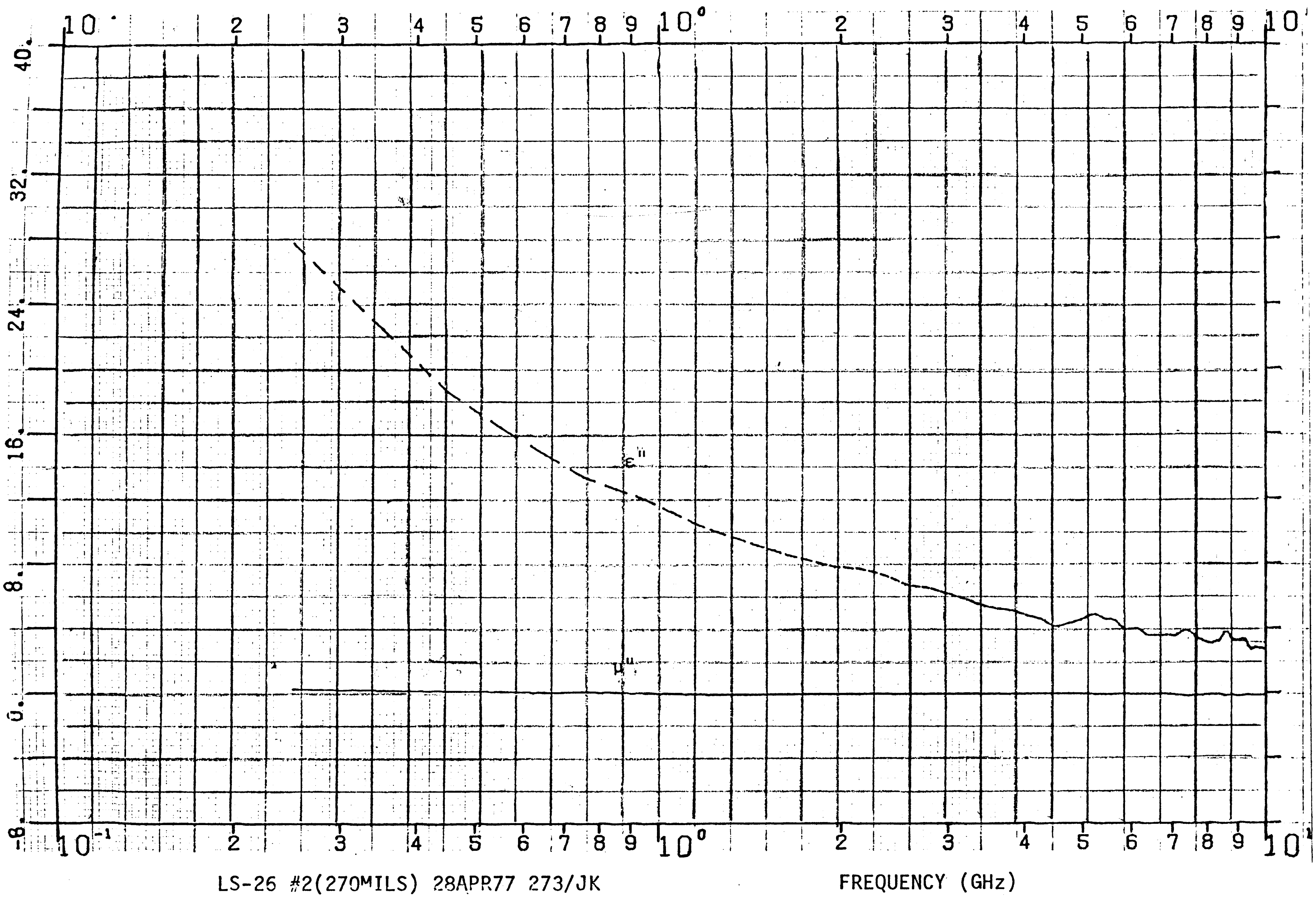


Fig. 2: Measured ε" and μ" of LS-26 material (Radiation Laboratory report 014449-1-F)

the effect of different geometries as well as different loadings. For this purpose, all that is required is a multi-layer reflection program. The material top-to-base is simulated by n homogeneous layers each of which has a permittivity which is the average of that provided by the corresponding section of the material. If, for example, in a given layer, the material occupies the fraction Γ of the total volume (the rest is air), the relative permittivity assumed is

$$\frac{\varepsilon}{\varepsilon_o} = 1 + \Gamma \left\{ 1.07\,(1-\gamma) + \gamma\,\frac{\varepsilon_c}{\varepsilon_o} \right\} . \tag{4}$$

The material which lies beyond the base of the pyramids can be represented as a single layer whose relative permittivity is given by (2), and beyond this there must be a metal backing. If ε_c were assumed independent of the frequency, the results would show the influence of different cone heights and geometries in relation to the total thickness of material and frequency.

Intuition suggests that if the material is loaded sufficiently, the reflection coefficient will remain almost constant with increasing wavelength (decreasing frequency) until λ becomes approximately 2h where h is the depth of the pyramids. If λ is increased still further, the shaping will no longer be sufficient to maintain a front face match, and the reflection will dramatically increase. If, in addition, the amount of material beyond the pyramids is insufficient to absorb the energy which penetrates, the reflection will increase still more, and in practice this problem is compounded by the fact that ε_c is itself increasing. To see this last point, suppose $\varepsilon_c = \varepsilon_c' + i\sigma/\omega$ with ε_c' and σ_c independent of ω. Then, for moderate loading at sufficiently low frequencies,

$$\frac{\varepsilon}{\varepsilon_0} \simeq 1.07 + \frac{i\gamma\sigma_c}{(\varepsilon_0\omega)} \tag{5}$$

implying

$$\sqrt{\frac{\varepsilon}{\varepsilon_0}} \simeq 1.03 + \frac{i\gamma\sigma_c}{(2\varepsilon_0\omega)} \tag{6}$$

so that

$$|R|^2 = \left|\frac{\sqrt{\varepsilon/\varepsilon_0} - 1}{\sqrt{\varepsilon/\varepsilon_0} + 1}\right|^2 \tag{7a}$$

$$\simeq \left|0.02 + \frac{i\gamma\sigma_c}{4\varepsilon_0\omega}\right|^2 \tag{7b}$$

$$\propto \frac{1}{\omega^2} \tag{7c}$$

if ω is sufficiently small. This represents a 6 dB per octave change and is a rationalization of the industry curve. However, this is not the only effect present, e.g., ε' also increases with decreasing frequency.

For most materials it is believed that the "breakpoint" occurs at $\lambda = 2h$ and as λ decreases below this the performance of the material degenerates at least as rapidly as $1/\omega^2$. Note that h is the pyramidal height and not the depth of absorber per se. The shape of the pyramids can also have an effect and we note that if the pyramids are cut "kitty corner" resulting in "obfuscated" pyramids, the depth of every other cavity is only about one half of the intervening ones. We believe this variant of the more traditional shape is electrically undesirable and largely a gimmick--to produce a shape which is visually more attractive for horizontal and vertical polarization without necessitating the mounting of the traditional pyramids in a diamond pattern on the walls, and to improve the structure integrity of the material. However, the achievement of very low frequency performance is a difficult enough challenge as it is, and there are other ways to get at the structural problem. We therefore believe (i) that the standard pyramidal shape should be employed, (ii) the pyramidal depth should be as large as feasible, possibly occupying as much as three-fourths of the depth of the entire material, and (iii) the remaining one-fourth constituting the base to which the pyramid is attached should be loaded more heavily if this is necessary to provide adequate absorption. This last would be quite feasible if, as we understand, the base is manufactured separately and glued to the pyramid.

We think it important to test out these concepts, and our contacts with absorber manufacturers do not lead us to believe that they themselves have performed these analyses. In particular, the real and imaginary parts of the relative permittivity of a typical loaded foam material should be established at a variety of frequencies, with special emphasis on the values below 100 MHz. Even more helpful would be a knowledge of the corresponding quantities for a dispersion of the loading (carbon?) particles, since this would enable the values for an arbitrarily loaded foam to be predicted from formulas such as (2). The multi-layer program could then be invoked to predict the reflection coefficients for different pyramidal geometries, and the results confined by actual measurements.

The knowledge would also permit precise experimental simulations using small scale models. In this connection we remark that provided the scaling laws are followed, scale modeling is exact. Thus, if the suffix m refers to the small scale (scale factor p) model values,

frequency:	$f_m = f/p \quad , \quad \omega_m = \omega/p$
wavelength:	$\lambda_m = p\lambda$
length:	$\ell_m = p\ell$
permittivity:	$\varepsilon_m = \varepsilon$ implying $\varepsilon'_m = \varepsilon'$, $\tan\delta_m = \tan\delta$
conductivity:	$\sigma_m = \sigma/p$

For a 1/8 scale model, p = 1/8. Note that the permittivity must be the <u>same</u> at the full scale and model frequencies, and this is the thing that is difficult to achieve. In the present instance where there is evidence that the permittivity of the loaded foam changes significantly at frequencies below 100 MHz or so it is particularly important that any simulation of the 20 MHz behavior should employ the correct electrical constants, e.g., by using a more heavily loaded material, and not just model the change in absorber size.

To conclude this section, it may be of interest to describe some recent experiences of ours with 6 ft. Plessey material. Having obtained a batch of this material from the Ford Motor Co., we applied it to the rear wall of an anechoic chamber used for precision surface field measurements over the frequency range $0.1 \leq f \leq 4.0$ GHz. The rear wall was previously covered with 4 ft Emerson and Cuming material, and we had hoped that by replacing it we would improve the performance below (about) 150 MHz. This did not happen, and in sweep frequency measurements of the surface fields on various targets we observed significant errors around 280 MHz that had not been there before. After a variety of diagnostic studies it was concluded that the stray reflection was coming from the rear wall of the chamber; and that the reflection increased significantly at frequencies just below 300 MHz, but decreased again below 250 MHz, prior to increasing rapidly below 150 MHz. In part of the 250 to 300 MHz range, it seemed that the material was providing no more than -10 dB performance.

We believe that this anomalous performance is due in part to the pyramidal shape. In an attempt to check this, we drilled 1/2 cm holes at various locations through one of the pyramids while still on the back wall, and inserted a field probe. The field was then measured as a function of frequency at incremental depths in the material. The data showed the differing manners in which the field is attenuated at various locations within the pyramid, and this method certainly constitutes a valuable diagnostic tool for measuring absorber performance. As a result of these data, we decided to modify the pyramidal shape by deepening two of the less deep faces of each pyramid using a hand saw. This has provided some improvement in performance, albeit not as much as we had hoped. Because of some urgent measurements which require the full time use of the chamber for the next two weeks, we have not had the opportunity to try other modifications to the pyramidal shape.

Deck

The proposed deck is a substantial structure about 1500 ft^2 in area and covering (at grade level) most of the electrically significant portion of the floor. Ideally the deck should be transparent (invisible) at all microwave frequencies of interest, and consistent with the need for a rigid deck, it is presently designed to have a low dielectric core with thin (20 mil) fibreglas skins and a 2 mil coating of paint. The overall thickness is 3.002 inches and the average value of ε' is 1.143 ε_0 approximately. At wavelengths which are much greater than this thickness, the deck should look like a thin layer having this average dielectric constant, and be reasonably transparent. Not so, however, at the shorter wavelengths where the reflections from the individual layers become significant, and as evident from the computed data obtained by Boeing using the multilayer program, the design is quite inadequate at all frequencies from about 100 MHz on up.

We believe these data to be valid and correct and typical of any rigid material strong enough to be walked upon. "Fiddling" with the permittivities and thicknesses of the various layers might reduce the average return by a few dBs at high frequencies, but the result would still be a structure which was electrically inadequate and which in large measure vitiated the expensive, laboriously installed, high performance absorber beneath it. The fact is that one is seeking a rigid material whose voltage reflection coefficient is less than one percent from a fraction of a GHz on up, and we are unaware that any such material exists. Radome technology supports this view, and transmissivities approaching 99 percent are achievable at most over narrow frequency bands.

It is our understanding that the sole purpose of the decking is to provide access to the three antennas. When the chamber is in operation, no personnel can be on the deck (or even in the chamber), and the antenna will be operated remotely. Thus, the access is limited to such occasional servicing, maintenance and adjustment of the antennas as are necessary. This seems a poor rationale for installing a large deck which will inevitable reduce the electrical performance of the room. Access to the antennas could be achieved just as well from a fibreglas platform 3 ft (or so) on a side supported by struts and wheels running on fibreglas rails 2 ft apart buried beneath the absorber (see diagram). The trolley could be electrically controlled and pulled back to the wall behind the antennas prior to any test. If necessary, two such sets of rails could be installed on either side of the antennas (on the center line of the chamber) with two trolleys to facilitate the servicing. If Ford Motor Co. would agree, this "solution" to the deck problem would be far superior to any other, and would be optimum from the electrical point of view.

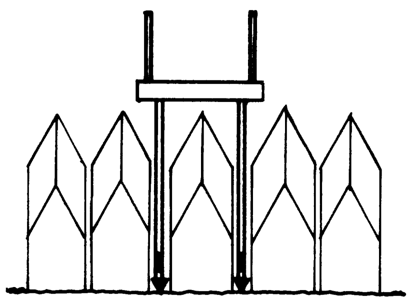


Fig. 3: Trolley concept in lieu of a deck.

If a deck of substantially the present form must be retained, there are two ways to reduce its influence on the quiet zone: (i) reduce the illumination of the deck, and (ii) eliminate the reflected rays which could penetrate the quiet zone. At frequencies approaching 20 MHz the deck is almost transparent, and it is therefore unnecessary to address the corresponding low band source. The other two sources (1 and 1-20 GHz) are both 7.6 m from the edge of the quiet zone. At these higher frequencies it would seem feasible to design the antennas to keep the illumination of the deck to a minimum, i.e., restrict the main beam of the 1 GHz antenna to the ± 15 degree angular range appropriate to the quiet zone, and the main beam of the high band source to ± 12 degrees. There are several ways in which the necessary control of the main beam and side lobes could be achieved.

If such "tampering" with the source antennas is not permitted, we are left with option (ii) as the only way to reduce the deck effects. For the high band source, an absorbing barrier or fence 0.9 m high placed 3.3 m from the source would prevent any reflected geometrical optics ray from entering the quiet zone, but would have a minimal effect on the 1-20 GHz signal. For the latter signal, a fence 1.1 m high 4.1 m from the source is necessary, but would block the illumination of part of the quiet zone by the high band source. Thus, each source requires its own fence and the fence for the 1 GHz would have to be removed before operating the 1-20 GHz source. This would be inconvenient at best, and possibly unacceptable. Moreover, any fence would produce diffraction, and create some perturbation of the quiet zone illumination by the very fact of its presence. For this reason we believe that the use of barriers is the least desirable approach to the deck problem.

A related problem is that of the turntable which certainly must be present. Without question, it will affect the field in the region above the turntable, but most EMI tests that we are familiar with require that the vehicle be on a "ground" of some known or specifiable properties. If this is the case, the problems of the turntable are due to its finite size, i.e., the edge contributions which perturb the field that an infinite structure would have. Recent tests by Boeing using the 1/8th scale model of the chamber have shown that the edges of the turntable do scatter, as expected.

Until the deck problem is resolved, it is impossible to pinpoint all of the offending edges of the turntable. Suffice to say that there are ways to reduce edge scattering by shielding and other appropriate edge treatments, and these can be explored when the time comes.

Acknowledgement

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List of Symbols

ε	Complex permittivity.
ε'	Real part of the complex permittivity.
ε''	Imaginary part of the complex permittivity.
ε_o	Permittivity of free space.
ε_c	Relative complex permittivity of carbon.
ε_c'	Real part of carbon permittivity.
ε_c''	Imaginary part of carbon permittivity.
γ	Loading factor by volume ($0 \leq \gamma \leq 1$).
γ_w	Loading factor by weight.
ρ	Material density (lb/ft^3).
ρ_c	Carbon density.
$\tan \delta$	Loss tangent of material.
$\tan \delta_c$	Loss tangent of carbon.
μ'	Real part of permeability.
μ''	Imaginary part of permeability.
Γ	Reflection coefficient.
σ	Material conductivity.
σ_c	Carbon conductivity.

Recommendations

Below are listed several recommendations that may be employed to optimize the performance of the Ford anechoic chamber:

1. Use best commercially available pyramidal shape absorber presently available.

2. Install the absorber on the chamber walls with the material rotated 45 degrees about its axis so that all flat surfaces are skewed 45 degrees to the transmitter-receiver axis of the chamber.

3. Install structures (foam black treated fire-retardant n cantilever rods) to minimize the drop in material of six feet long and longer.

4. We have no recommendations regarding the painting of the absorber.

5. Employ a removable deck structure.

6. Treat turntable edges by serrating and/or rounding them and cover all sides with absorber material.

II
MATERIAL CONSIDERATIONS

2.1 Definition and Application as Target Supports

A foam is simply a collection of bubbles or cells, each of which is bounded by thin walls of more or less irregular shape. The cell walls enclose a gas, which need not be air, and the foam structure is called unicellular if every cell, save those on the very boundary of the mass, shares all its walls with neighboring cells. An open-cell structure is one in which the gas is not partitioned in separate pockets; in this kind of foam, the cells are interconnected. The degree of interconnection is usually specified as "percentage open cell structure". A multicellular foam is composed of relatively large cells, each of which houses an independent colony of finer cells, usually of unicellular structure.

Cell walls are planar, rigid and a typical thickness is 0.0002 inch for a typical cell diameter of 0.02 inch. Cell diameters vary from material to material and from cell to cell within a given material. Distribution of cell diameter has apparently not been studied in detail, but it seems that the most common size is the geometric mean of the largest and smallest sizes that can be found in a given block of foam. Cells may be as small as 0.002 inch in the urethanes to as large as 0.06 inch in the (useful) polystyrene foams. There are foams which have cells as large as 0.5 inch, but these are decorative materials ill-suited for target support applications.

Of the unicellular foams, Styrofoam[+] was probably the best known and most widely used for early target support requirements. It was practically invisible to the radar, was rigid enough and strong enough to support most of the models, and was easily worked. Its density was very low: it weighed from 1.5 to 2.0 pounds per

[+]This is the registered trade mark for an expanded polystyrene foam produced by the Dow Chemical Company, Midland, Michigan.

cubic foot (pcf) since its volume was nearly 98 percent gas. It has become the classical support material and even now is probably more widely used than any other. The advent of low cross section shapes of large physical dimensions caused people to look into other model support schemes since Styrofoam,* while virtually invisible, was not invisible enough. An early competitor for the job was the string which could easily be made a magnitude or more smaller (in radar cross section) than the best foam, but which was not without its disadvantages. More recently, several exotic support schemes have attracted attention: spin dropping, air jets, magnetic fields, and air bags are among the latest ideas. In spite of these schemes, rigid foam materials remain the most widely used. In those cases for which foam is the only feasible support method, techniques have been developed which remove or compensate for target support effects (Hiatt et al, 1963).

2.2 Types of Rigid Foam and How They are Made

There are nine commercially recognized types of foam, of which seven may be classed as rigid:

- cellulose acetates
- epoxies
- polystyrenes
- silicones
- urea-formaldehydes
- urethanes
- vinyls

Of these, the polystyrene foams, and perhaps the urethanes, are the most familiar to the target support designer. The styrene foams are available in two forms, expanded and expandable bead. The former is an extruded foam while the latter is molded.

Styrofoam is produced by dissolving polystyrene in a solvent such as methyl chloride and subjecting the resulting gel to heat and pressure. The gel is permitted to escape through an orifice and the sharp drop in pressure causes the heated solvent to flash into vapor, creating bubbles. A "take-away" table removes the frothing mass at the proper speed. A cooling period follows during which the outermost cells harden first and the interior cells last. The final cell size and density is determined by several variables, among them the raw materials, take-away speed, pressure, etc. The differential cooling rate (from surface to interior) produces a variation in cell size which can be as great as 5:1 or 10:1, the interior cells being the larger. Better uniformity than this is possible if thinner cross sections are extruded. The material near the surface hardens first, hence the cells there have little chance to grow while those in the core may expand considerably before enough heat is removed from the mass. Presumably the fire-retardent properties and colors (Styrofoam can be made blue or green as well as white) are imparted with the necessary additives prior to extrusion. The cell structure tends to be elongated in the direction of extrusion and ratios in dimensions of 2:1 are not uncommon. The anisotropy causes physical properties to vary with the direction of the applied stresses. Occasionally one finds a sizable chip or sliver of wood embedded in the log; the presence of foreign matter such as this, as well as other inhomogeneities, is not usually detectable until exposed by a fresh cut through the log.

The molded foams first appeared in 1954 (Randolph, 1960). These are expandable bead foams and the process begins with small beads which contain not only the polymer but the expanding agent ("blowing" agent is the name used in the trade) as well. The pinhead-size beads require a two-stage expansion, the first of which is called pre-foaming. This step is accomplished by exposing the beads to any form of heat, ranging from infra-red lamps to live steam, and is halted when the bulk density of the pre-foamed beads matches that of the volume desired to be fabricated. The pre-foamed beads are typically 1/8 to 1/4 inch in diameter and must be stored for a period of 1 to 14 days prior to to the final foaming process.

Final foaming is done in a steam heated mold which must be constructed to withstand typical steam pressures of 20 to 35 psig. Large volumes must be produced by the insertion of perforated steam pipes into the mold cavity; after foaming, the pipes are quickly withdrawn and the residual heat in the mass causes the beads to fill the voids left by the pipes. This may produce some local variations in density which cannot be avoided in large volumes. When molding small volumes, a convenient heating arrangement is a steam jacket encasing the mold. Another scheme provides a perforated jacket, which permits the steam to seep through the volume. Expandable bead foams can be produced with densities as low[+] as 1.1 pcf, while 1.5 pcf is more common for Styrofoam.

Urethane foams do not depend on the application of heat for the foaming process, but upon the evolution of gases formed by an isocynate-fluorocarbon reaction. In commercial production, elaborate mixing fixtures bring together the reacting compounds and deposit them in a suitable mold. The molds may be open at the top and thus need not be as strong as those required for the pre-foamed polystyrene beads. The reaction is accompanied by the evolution of heat, which may become a problem if very large volumes are desired, and takes place in a matter of minutes. The foam is permitted to rise and the material near the bottom will be more dense than that near the top. Generally, a few inches of the material can be removed from the surfaces of the volume after withdrawal, leaving a substantially uniform density core. As with polystyrene foams, urethane foams may be anisotropic because of the direction of rise. Densities as low as 1.5 pcf are attainable (Stengard, 1963).

Other foams are known to be produced, such as epoxy foams and polyvinyl chloride foams, but little has been done with these as regards target support applications. It is probable that they are no better, perhaps worse, than the classic Styrofoam, since the dielectric constant of the base polymer may be 35 percent greater than that of polystyrene while the strength may be 20 percent less.

[+] Recently, a representative of The Armstrong Cork Co., Lancaster, Pennsylvania, stated that densities as low as 0.5 pcf have been achieved.

2.3 Description and Comparison of Foams

Expanded polystyrene, of which Styrofoam is probably the widest known, first appeared commercially in the United States in 1944 (Randolph, 1960). It is presently available in billet or board form and is sold for insulation, toys, novelties and construction. The larger billets, known in the trade as "logs", may come in several sizes. The largest, and usually the most difficult to obtain, is about 2 feet by 3 feet in cross section and 9 or 15 feet long. The surface is heavily corrugated and cracked, which is an unfortunate consequence accompanying the extrusion of large cross sections. These cracks make it impossible to fabricate a circular column much greater than 19 inches in diameter. The next size log is 12 by 29 inches in cross section, 9 feet long and has a smooth, tough skin. The skin is under stress and if it is sliced off, the core of the log will immediately shrink about an inch along the 9-foot dimension. This property renders fabrication processes difficult and unless care is taken, a column fashioned from this log is likely to be deformed.

Expandable bead polystyrenes are familiar to practically everyone. These are the foams that may be found in low-cost ice chests, floats, toys and uncountable other items. While not of importance for radar purposes, it can be dyed and beads of different colors may be mixed for decorative effects. The foams are multicellular and are available in logs as large as 16 inches by 48 inches in cross section and 9 feet long. The material is cut easily and cleanly by hot-wire techniques and has low density. The density can be controlled to a much greater degree than the extruded styrene foams due to the ease of control during the pre-foaming operation. Logs of expandable bead foam lack the skin found on extruded polystyrene. It is conceivable that they can be manufactured in circular as well as rectangular cross sections.

Urethane foams have strikingly uniform cell size distributions compared with those of the polystyrene foams. They can be unicellular and generally can be had with relatively small cells. Common colors are white, yellow and tan. Urethanes are considerably weaker than the polystyrenes when compared on an equal density basis. Construction of large volumes is possible but there is a danger of damage by the heat of reaction if the core cannot be sufficiently cooled.

Of the remaining foams listed on page 4, no attempt has been made to determine sizes available or to describe them further, except as summarized in Table I. It is felt that these materials are not important in the light of target support requirements and do not warrant any further attention here.

Foam properties are usually presented as functions of density, which is an easily measured parameter, and since strength and dielectric constant are two important properties to consider in target support design, it is useful to relate column radar cross section to density. A convenient shape for discussion is the right circular cylinder: if it is illuminated with a wave polarized parallel to the cylinder axis, and if $d \gg \lambda$, the cross section will be periodic with frequency and will reach maximum values[+]

$$\sigma = \frac{1}{8} kd \ell^2 \left(\frac{\epsilon}{\epsilon_o} - 1\right)^2$$

(see equation 23), in which

d = cylinder diameter

ℓ = cylinder length

ϵ = dielectric constant for material

k = propagation constant of free space

The assumption has been made that the column will be used for several frequencies so that one cannot select a diameter favoring the cancellation of front and rear surface returns.

[+]It is here assumed that the dominant return is the coherent one produced by the exterior surfaces.

The presence of d in the expression suggests that the smallest diameter possible should be used, which in turn suggests the column will be a slender one. Hence the column is expected to fail by buckling rather than be excessive compression under load. The critical load at which the column will fail is (Timoshenko and MacCullough, 1949)

$$P = \frac{\pi^3}{256} \frac{Ed^4}{\ell^2}$$

where E is the modulus of elasticity of the material. The worst case (i.e., most conservative) has been assumed, namely that one end of the column is fixed, being capable of sustaining moment, and the other end free. Thus, the minimum diameter required for a given load P has been established and can be used in the expression for cross section.

Considering now the dielectric constant, a simple approximation in terms of density can be written

$$\epsilon \simeq \epsilon_o(1 + \alpha\rho),$$

where α is a constant depending upon the density and dielectric constant of the base polymer and ρ is the foam density. The approximation yields somewhat larger values of ϵ than measured data indicates (Cuming and Andress, 1958; Myshkin, 1958), but is adequate for this discussion. If the above values for d and ϵ are used in the expression for cross section, there results

$$\sigma = \frac{k\ell^{5/2}P^{1/4}}{2\pi^{3/4}} \frac{\alpha^2\rho^2}{E^{1/4}} .$$

Thus the best foam, given a frequency, load, and column length, is the one which has the smallest value for $\alpha^2\rho^2/E^{1/4}$.

It is tempting to try to further improve the expression by finding the relation between E and density but this leads to many complications. The primary objection is due to manufacturers' listed data, which rarely specify properties but instead present ranges in values that bracket the expected foam properties. Another is that the modulus of elasticity generally varies inversely with cell size, requiring one more piece of information for a materials comparison. In addition, the foam becomes plastic for relatively small loadings and the description "modulus of elasticity" seems inappropriate.

Fortunately, the cross section is in terms of the square of density but only the fourth root of E. This means that variations in E will have a much smaller effect than variations in ρ. Hence a very rough judgment of the relative radar performance of foams can be made by inspection of their densities. Generally, the lowest density foams make the best target support columns. The presence of α^2 in the expression suggests that for a fine comparison of materials, the properties of the base polymers must be studied as well as foam density and elastic modulus. Table I summarizes some of the properties that can be expected of commercial foams (Hodgman, 1958; McCann, 1962).

TABLE I: SOME PROPERTIES OF COMMERCIAL FOAMS

Foam Type	Density, pfc	Tensile Strength, psi	α of base polymer
Urethane	1.5 - 3.0	15 - 70	----
Polyvinyl chloride	3 and up	10 - 200	3 - 4
Cellulose acetate	6 - 8	170	3.2 - 7.0
Urea-formaldehyde	0.8 - 1.2	poor	6.7 - 6.9
Polystyrene (bead)	1.0	33	2.50 - 2.65
Polystyrene (extruded)	1.8	55	2.50 - 2.65
Epoxy	5 - 20	55 - 500	3.5 - 5.0

2.4 Foam Manufacturers

Table II is a list of some foam manufacturers in the United States. The list is by no means a complete one, but it does include some of the larger and better known producers. Those which are marked by an asterisk (*) have been solicited by this laboratory for product information.

TABLE II: PARTIAL LIST OF FOAM PRODUCERS

Manufacturer	Product	Trade Name
*Dow Chemical Co. Midland, Michigan	Expanded polystyrene (extruded)	Styrofoam
	Expandable bead polystyrene	Pelaspan
	Urethane	Thurane
Armstrong Cork Co. Lancaster, Pennsylvania		-------
Emerson and Cuming, Inc Canton, Massachusetts	Expandable bead polystyrene	Eccofoam PS
Koppers Company, Inc. Pittsburgh, Pennsylvania		Dylite
*Atlas Chemical Co. Wilmington, Delaware		----
*Wyandotte Chemical Co. Wyandotte, Michigan	Urethane	-----
Nopco Chemical Co. Newark, New Jersey		-----
*Ciba Products Co. (Div. Ciba Corp.) Fair Lawn, New Jersey	Epoxy	-----
*Shell Chemical Co. (Plastics and Resins Div.) New York, New York		------

2.5 Survey

Several organizations and individuals were contacted, either in person or by letter, in an attempt to survey previous work on foam materials. None had information for foams other than polystyrenes or urethanes. The survey results are presented below.

MIT Lincoln Laboratory (Peter Fritsch)

Fritsch measured a Styrofoam cylinder at K_a-band frequencies using diameter-to-wavelength ratios from 7.6 to 8.7. The measurements verified the periodic nature of the return with frequency and showed the maximum cross section to be about $4\lambda^2$. The periodicity agreed with that calculated for a dielectric sphere of dielectric constant 1.05.

Lockheed Missiles and Space Company (N.J. Gamara)

Lockheed had no helpful data available.

GM Defense Research Laboratories (W.P. Melling)

Melling reported he had no organized data although some measurements had been made of foam columns of various diameters. He said that DRTE had measured the returns from Styrofoam and Eccofoam, and the periodic nature was observed. They (at DRTE) had found shaping to be unsuccessful and that no foam was superior to Styrofoam.

Canadian Defense Research Telecommunications Establishment (John Keys)

Keys confirmed that DRTE had concluded grooving or fluting a column offers little advantage over a smooth one. He had no organized data to present, but noted than Emerson and Cuming's foam was a little better than Styrofoam. He reported that an aged column is somewhat better than a virgin one; they expose their columns to direct sunlight to speed up the aging process.

Radiation Incorporated (J.E. Landfried)

This organization has compared the return of several foams and found no improvement was gained by shaping or serrating the columns. No foam was better than Styrofoam but there were inhomogeneities whose effects were more severe at the higher (K_a-band) frequencies. Scattering from sample to sample was not consistent.

B. F. Goodrich Company

Goodrich, in its evaluation of the anechoic chamber it built for Sperry, conducted measurements of several kinds of columns, varied in both shape and materials. The data presented in the report suggests low density foams are the best and that tapering is helpful. Serrations or grooves seem to be beneficial if the resulting edges are orthogonal to the incident radiation.

University of Michigan (Harold Borkin, Architect)

Mr. Borkin is qualified to discuss foams since he studied them in connection with low cost housing. He feels that urethane foams may be worthy materials since they are available in large volumes and can be tailored to yield densities from 1 to 20 pcf. The high dielectric constant expected of high densities may be offset by their superior strengths.

Conductron Corporation (Howard Brooks)

Conductron has found the expandable bead foam, Pelaspan, superior to Styrofoam, although their data is not organized. The material is easily cut by hot-wire techniques and is available in logs of respectable size.

Ohio State University (E.M. Kennaugh)

Some of the O.S.U. efforts are contained in their reports. Generally, Styrofoam is found to be the best material for support of models and antennas. One of the reports deals with the effects of interfaces, for example, while others discuss scattering from dielectric bodies. O.S.U. has not made a study of foams, per se.

It can be seen that among those surveyed there is a difference of opinion. Most assert that shaping or serrating the columns makes little difference, yet one source suggests shaping is advantageous if the incident polarization is in the right direction. Most of those surveyed indicate there is nothing better than Styrofoam, yet there are two who have found something they consider better. Note that those who found something better have studied the expandable bead polystyrene foams.

USE OF NEAR FIELD PROBING TO DIAGNOSE THE (POOR) PERFORMANCE OF PYRAMIDAL-TYPE ABSORBING MATERIALS

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The use of near field probing is presented as a diagnostic tool in determining the performance of the absorber and optimizing the absorber design for best performance. For relatively high frequency absorbers this can be accomplished and evaluated by measuring the backscattering from individual two-foot pieces, but when the absorber thickness is measured in feet and test frequencies are in the 100 MHz range, the backscattering measurements many times are not feasible. On the other hand, the near fields can be probed and by knowing the field behavior inside and in the vicinity of the absorber much can be learned about the absorber behavior.

During the summer of 1981 we had an opportunity to acquire six-foot pyramidal absorber to replace the four-foot pyramids on the back wall in our surface field measurement facility. According to the accepted standards this absorber should lower the operating range of the chamber to at least 100 MHz. However, after the installation of the new absorber we found the chamber performance to be worse than before with the 48-inch pyramid material. We then proceeded to employ the near field probing to measure the fields in the region between the tip and the base along various trajectories along the pyramid, all as a function of frequency. Data are presented to show that along certain trajectories the field is actually increasing toward the interior of the pyramid, indicating an apparent reflection of the incident wave. From analysis of this data changes in geometric shaping were deduced and made. Similar measurements were then repeated and these show a substantial improvement of the field behavior inside the pyramidal region.

Finally, the field was recorded as a function of frequency and position in the quiet zone regions and from these data the effective reflectivity of the absorber was deduced.