Abstract— RF shielded enclosures have been common features in laboratories and manufacturing areas for over 70 years. They provide a quiet environment where RF measurements can be performed without interference from outdoor sources and are used to keep potentially classified frequencies and modulations from leaking out. In general, these shielded rooms have shielded doors to maintain the shielding integrity of the enclosure until they are opened. In some cases, to maintain the shielding integrity as personnel moves from the inside to the outside of the room and vice-versa, dual shielded doors with a small vestibule between them are used. However, the presence of multiple doors increases the time to access the enclosure. To solve this, some enclosures are designed featuring access passages to maintain the shielding integrity over a broad frequency without the use of doors. Although this type of access has been around for over 40 years, its design has never been discussed in the literature. In this paper, a door-less access is analyzed and some design rules are presented. The limitations of these accesses are also presented. While clearly they do not have the shielding performance of a shielded door, they are ideal for certain applications.

Keywords: Shielded enclosures, door-less access

I. INTRODUCTION

The use of shielded access passages to enter large shielded enclosures goes back almost 40 years [1]. These passages have their niche in large shielded buildings that have to be accessed by a multitude of people. Even if the entire building is not shielded, there may be significant areas of the building that need shielding. The personnel that work inside these areas must be able to move freely between parts of the building, going from the shielded area to unshielded areas of the building.

One common approach to maintain the shielding integrity as people access the area is to have a set of two doors separated by a vestibule. Persons leaving the shielded area will open the first shielded door (Figure 1 a) and access the vestibule. The second shielded door is closed; keeping the shielding effectiveness of the area. Persons leaving close the first door (Figure 1 b) and proceed to open the second one. The first door maintains the shielding effectiveness as the second door is opened (Figure 1 c). This is an effective way of solving the problem of continuously keeping the desired shielding effectiveness (SE) of the enclosure. However, it is clear, that this is a time-consuming approach and there must be a way to avoid the problem of the first and second door being opened at the same time as personnel try to both leave and access the area, as shown in Figure 1 d).

The use of automated doors can help these issues. Controls can be used to avoid both doors being opened simultaneously. However, these automated doors can be slow in opening. Some of them use pneumatic bladders that inflate to keep the contact between door and frame; while others only unlatch and push the door open to where it no longer contacts the frame, but still need to be manually opened.

To solve these issues, the concept of the shielded access passage was developed. In [1], the word “labyrinth” is introduced for these access corridors. The name probably came from the number of turns necessary to maintain an attenuation of signals through the passage. The theory behind the use of these passages can be divided in three. The first is to use the cutoff of a waveguide (in effect the cross section of the access) to shielded...
the lower frequencies. The use of RF absorber is the second part, as it makes the waveguide a lossy transmission line where the signals are being attenuated. This second theoretical background is used to help with the middle range of frequencies. In this paper, a closer view is taken on this theoretical approach to “Labyrinth” design. The limitations and errors of these assumptions are discussed. Numerical solutions are presented in some cases to support our claims on the limitations of the traditional approach.

<table>
<thead>
<tr>
<th>Attenuation in the access passage</th>
<th>Frequency range</th>
<th>Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low frequencies</td>
<td>(under 100 MHz)</td>
<td>Cut-off of the passage cross section, attenuation of evanescent waves</td>
</tr>
<tr>
<td>Mid Range</td>
<td>(100-500MHz)</td>
<td>Lossy material lining the walls of the passage. Transmission line losses</td>
</tr>
<tr>
<td>High range</td>
<td>(500MHz and up)</td>
<td>Turns on the passage. Normal incidence attenuation of absorber.</td>
</tr>
</tbody>
</table>

II. SHielding Effectiveness

If the goal is to get certain level of shielding effectiveness (SE), it is important to define how we are to quantify this parameter, including a measurement methodology. If possible, the same approach should be used to model sections of the access passage and to quantify the SE. Luckily, there is clear documentation that defines the approach to measuring SE. The most popular is IEEE STD 299-2006 [2]. In [2], the typical approach for measuring SE is described. As shown in Figure 2, the approach is place two antennas at a given distance (D), and measure the transmission between them. This is the reference for the measurement. The measurement is repeated with the antennas separated the same distance, but with the shielded structure in between them.

In the numerical models that are presented, we use a similar approach as shown in Figure 3. A reference measurement is performed using two small biconical antennas. The S21 from this simulation becomes the reference of unshielded performance. The simulation is then repeated, but with the shielded structure. The shielded structure simulated can be a section of passage or a turn on the passage. When modeling the passage, a ground plane of PEC is added under the antennas. The antennas are placed 1.64 ft (50 cm) away from the opening of the passage and at half the height of the passage over the ground plane. Modeling the full passage up to 1 GHz is extremely costly, but it is possible to model sections and cascade their performance. The difference in transmission between the two antennas (S21) with and without the structure in between is the SE of the structure. This approach is similar to the measurement approach described in [2].

Figure 2. The shielding effectiveness measurement. The calibration or leveling is shown above. Then the SE measurement is repeated below.

In equation (1), \( a \) is the dimension perpendicular to the field polarization. If we assume the walls of the passage are made of steel, we can then get the expected attenuation for a 4ft section

\[
f_{c_{01}} = \frac{1}{2a\sqrt{\mu}}
\]
of passage. The cut-off when the field is vertical is at 86.79 MHz, while for the horizontal case the cut-off is at 61.47 MHz. Table II shows the attenuation that can be achieved for a 4 ft section without the absorber lining the structure.

Table II. Attenuation of the evanescent modes in the passage.

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Vertical field Attenuation for 4 ft (dB)</th>
<th>Horizontal field Attenuation for 4 ft (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>18.08</td>
<td>11.9</td>
</tr>
<tr>
<td>50</td>
<td>15.75</td>
<td>7.94</td>
</tr>
<tr>
<td>60</td>
<td>13.9</td>
<td>2.97</td>
</tr>
<tr>
<td>61.47</td>
<td>-</td>
<td>0.283</td>
</tr>
<tr>
<td>70</td>
<td>11.4</td>
<td>0</td>
</tr>
<tr>
<td>80</td>
<td>7.47</td>
<td>0</td>
</tr>
<tr>
<td>86.79</td>
<td>0.1</td>
<td>0</td>
</tr>
<tr>
<td>90</td>
<td>0</td>
<td>-</td>
</tr>
</tbody>
</table>

As it can be seen below cut-off, this passage could have a shielding effectiveness of more than 40 dB for a 16 ft section. This reasoning is given in [1]. This, however, only tells part of the story. Recall that to help the middle frequency range, we must add absorber to the walls and ceiling. Adding the absorber loads the waveguide and shifts down the cut-off frequency. The new cut-off as given in [3] is

\[
\frac{1}{2a\sqrt{\varepsilon_d}} \leq f_c \leq \frac{1}{2a_0\sqrt{\varepsilon_d}}
\]  

(2)

That is, the cutoff frequency fall between the cutoff of a waveguide filled completely with absorber and a vacuum or air waveguide. We estimate the pyramidal absorber to be equivalent in volume to a block 1/3 the height of the pyramid as has been done in [4]. Then using the fact that typical 12-inch pyramidal foam has an \( \varepsilon_r \) of about 30 at 60 MHz, the wavelengths inside the foam are about 5.4 times shorter. Thus, the tunnel appears about 18” taller and 36” wider at 60 MHz, moving the cutoff frequency for the horizontal case down to 51.7 MHz. As reported in [5], longer absorber has a lower permittivity. Using longer absorber however means the cross section of the passage has to be larger to accommodate both the absorber and leave clearance for people to use the passage. The larger cross section pushes the cut-off frequency further down and makes it more difficult to achieve attenuation above cut-off since then we depend on the lossy properties of the absorber.

The mid-range of frequencies is the most difficult issue to solve. A typical passage will have a cross section of about 8 ft x 8 ft or 8 ft x 6 ft to allow for easy access of equipment and personnel and also to meet the requirements of other standards, and guidelines, such as those in [6] that regulate the minimum clearance for wheelchair accessibility. For example, [6] requires a 60 in. clearance from wall to wall for a corridor where two wheelchairs may cross each other.

Based on this, let’s assume that our corridor will be 8 ft x 8 ft in cross section. From equations (1) and (2), it can be seen that the cutoff will be slightly lower than 61 MHz. The walls and ceiling of the corridor will be lined with 12-inch absorber. This will leave a wide enough clearance to meet the requirements of [6]. The floor will be left untreated to make it easier to move heavier loads and also to allow for wheelchair traffic. When a simulation is performed on a 14 ft section of the passage, the shielding effectiveness shown in Figure 5 is obtained.

One must be careful interpreting the results shown in Figure 5. Between 50 and 70 MHz, the coupling between the antennas is higher than it was in the reference. This yields a shielding level higher than 0 dB. Recall that the passage is working as a transmission line. Clearly at that range, whatever small attenuation the absorber is providing is not enough, and the waveguide is helping to transmit more power to the receive antenna. The data show the difficulty of getting a good shielding effectiveness with these passages between 30 and 100 MHz. The use of turns will be required to achieve any usable level of shielding at those frequencies.

One option is to use a hybrid absorber. Hybrid absorber using a carbon loaded foam over a ferrite tile is very common in EMC applications. This type of absorber has limitations at higher frequencies due to the use of a foam with a lower carbon content to better match the ferrite [7]. Since the profile of the ferrite tile is only 0.24 in (6 mm), for this simulation tile will be placed on the floor. It is possible to have this tile on the floor covered by
epoxy paints to be able to roll heavy loads and walk over it without breaking the fragile tile.

Figure 6 shows the performance of such a straight section of tunnel lined with an 8-inch tall truncated pyramid over ferrite tile and ferrite tile on the floor.

![Figure 6. A 14 ft section of the passage with 8-inch hybrid truncated pyramidal absorber and ferrite tile on the floor. The inserts show the simulated model and the field distribution at 80 MHz.](image)

The data in Figure 6 shows that the use of the hybrid absorber provides much higher numbers of attenuation than standard absorber. Notice, however, that as the frequency increases, the effectiveness of the straight section is reduced. As it will be shown in the next section, turns will provide the desired levels at higher frequencies into the microwave range.

IV. FULL WAVE ANALYSIS OF TURNS

As mentioned in Table I, the high frequencies will depend on the turns and, to be more precise, the absorber that lines the back wall of each turn. It could be tempting to immediately approach the problem by using the longest possible absorber available - the one that will have the best performance at the lowest possible frequency to help the attenuation of the mid-range, which we observed is limited in the straight section of the passage. Using the longest material may not be necessary, and it may be a waste of space and money.

To analyze this problem, a series of turns were analyzed using CST Studio Suite™. As it was done with the straight sections, a reference transmission was done between two biconicals in free space, as shown on the top section of Figure 3. Then the turn was placed in the simulation and the antennas placed to be half the distance to the entrance of the turn. An additional wall of PEC was placed between the antennas to cut any possible coupling between them. So the only path for the energy to transmit from one to the other is through the turn. Figure 7 shows one such simulation model. In Figure 8, the field distribution is shown for the two principal polarizations at three different frequencies.

As stated above, it could be tempting to use the largest possible absorber. However, the simulations for typical sizes show that as the absorber size increases, the improvement is marginal at best. Hence, there is no advantage from using a longer pyramidal absorber on the turns to achieve better shielding at the turns of the access passage. Figure 9 shows the shielding results for all these different turns with different absorber lengths treating the end walls of the turn. The geometries being analyzed are shown in Figure 10.

![Figure 7. A simulation of a single 180 degree turn. The top of the model has been sliced to show the absorber walls. Notice the shield wall between the two antennas.](image)

![Figure 8. Field distributions for a turn on an 8 ft x 8 ft cross section corridor with 12-inch absorber on the walls and the ceiling.](image)

Notice that there is not much difference in performance between a 6 ft piece of absorber and a 3 ft piece. Both have very similar performance at 100 MHz, but the use of 6 ft pyramids requires 48 sq. ft. of extra space to be implemented at every turn.

At this point we can cascade the performance of this section to design an access passage with certain levels of shielding effectiveness. To verify if cascading is acceptable, a simulation of a double turn is performed. If we compare the results for a single turn with 12-inch absorber on the end walls (Figure 9), with the double turn results (Figure 11), we see that the performance has significantly improved. At 100 MHz, the computed SE went from 14 dB at 100 MHz for the vertical polarization on the single turn to 27 dB at 100 MHz for the two-turn model. For the vertical polarization the SE changed from 22dB at 100MHz to 45dB at 100MHz for the two-turn model.
Based on those results we can say that cascading the results of the different simulations is an acceptable approach. Figure 12 shows the plan view of one of these shielded passages. It has two straight sections treated with hybrid absorber and a total of four turns with 24-inch material on the back wall of the turn.

The design proposed is clearly intended to give the best possible performance while meeting certain requirements for clearance and ability to bring heavy loads into the shielded area. The following table shows the expected levels based on the different simulations executed. The calculation assumes two straight sections of hybrid absorber that are 14 ft in length and four turns with 24-inch pyramidal. The cut-off frequency is expected assumed to be 50 MHz, based on the cross section of the passage and the absorber loading.

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Shielding Effectiveness (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤40</td>
<td>&gt;100</td>
</tr>
<tr>
<td>51</td>
<td>-55</td>
</tr>
<tr>
<td>60</td>
<td>-52</td>
</tr>
<tr>
<td>80</td>
<td>-90</td>
</tr>
<tr>
<td>≥100 and above</td>
<td>&gt;100</td>
</tr>
</tbody>
</table>

The results show that the range between the cut-off and the 100 MHz mark is a difficult range to achieve SE numbers in the 100 dB level. Even as we approach the cut-off frequency from below, the evanescent waves can propagate with attenuation. And if the tunnel is not long enough, then the SE will be compromised. These results show that this particular approach is better suited to shield at higher frequencies. If the critical frequencies where the work is being performed inside the shielded enclosure are above 1 GHz, these passages are economically feasible as an entrance to the shielded enclosure.
V. CONCLUSIONS

The paper has shown some of the theory and approach to the design of shielded access passages that was not available in the literature.

While shielded access passages or “labyrinths” are not a solution for all cases, they have a niche in areas where there is a continuous flow of people from the shielded enclosure to the outside and vice-versa. This approach also provides better access for people with disabilities and for moving heavy loads, such as racks of equipment, since there are no high thresholds on the path. High thresholds are required in some shielded doors to achieve the proper shielding requirement. Shielded access passages are very rarely going to exceed the performance of shielded doors unless an extremely large area is reserved for their implementation.

The use of hybrid absorber provides a significant benefit at some frequency ranges. However given the higher cost of this material, it may be desirable to minimize its use to straight sections of the passage. Longer absorber is not always the best choice, as it requires a larger footprint for the passage without increased shielding performance.

The basic rules of design are defined, but care must be taken to understand the effects of the absorber loading on the frequency cut-off as well as on the performance of turns used at higher frequencies to achieve the attenuation.

REFERENCES


314