Attenuating Tunnels for Accessing Shielded Enclosures

Vince Rodriguez
NSI-MI Technologies
Suwanee, GA, USA
vrodriguez@nsi-mi.com

Abstract—RF shielded enclosures have been common features in laboratories and manufacturing areas for over 70 years. They provide an environment where work on RF can be performed without interference from outdoor sources. These shielded rooms and areas provide a place where classified frequencies and modulations can be used without leaking out. In general, these shielded rooms have shielded doors to maintain the shielding integrity. These happens until they are opened. 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. This type of access has been around for over 40 years but 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 tunnels are also presented. They do not have the shielding performance of a shielded door but they are ideal for certain applications.

Keywords: Shielded enclosures, door-less access

I. INTRODUCTION

The use of tunnels or labyrinths to enter large shielded enclosures goes back almost 40 years [1]. These passages have their niche in large shielded buildings occupied by a large number of people. These people performing tasks inside the shielded enclosure may have to continuously move from within the secure area to non-shielded areas.

One common approach to maintain the shielding integrity of the area as people access the area is to have a set of two doors separated by a vestibule. The approach is as follows. The person leaving the shielded area will open the first shielded door (figure 1 a) and access the vestibule. The second shielded door is closed and it keeps the shielding effectiveness of the area. The person leaving then closes the first door (figure 1 b) and then proceeds 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. This is a time-consuming approach. It requires two sets of shielded doors. These shielded doors have thresholds and there must be an electronic control systems 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 on figure 1 d).

Additionally, 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. Furthermore, the door is the critical point in a shielded enclosure, and it requires periodic maintenance to check the knifes and copper fingers that provided the contact and shielding. To avoid these issues of thresholds, controls, and maintenance, the concept of the shielded access passage was developed. In reference[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 main points:
- Use the cutoff of a waveguide (in effect the cross section of the access) to shield the lower frequencies.
- Use RF absorber to make the waveguide a lossy transmission line. This handles the middle range of frequencies.
- Use of 180 degree turns to use the end wall of absorber to attenuate higher frequencies.

The points above are shown in the following table.

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

In this paper, a closer view is taken on the theoretical approach to “Labyrinth” or attenuating tunnel 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.

II. SHIELDING EFFECTIVENESS.

The goal is to achieve a given level of shielding effectiveness (SE). This parameter of SE must be quantified. Luckily, as most EMC engineers are aware, there are some clear documents that define 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 below a similar approach is used. The numerical approach is shown in figure 3. A reference measurement is done using two small biconical antennas. The S21 from this simulation becomes the reference or 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 50cm 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 1GHz is extremely costly, numerically speaking. Sections are modeled and their performance, cascaded.

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](image2.png)

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

![Figure 3](image3.png)

Figure 3. Views of the numerical models for the reference and the shielding simulation of a section of the passage.

III. DESIGN OF A TUNNEL

As shown in Table I, the approach to shield for the lower frequencies is to use the cut-off frequency of the passage itself. Using the cut-off frequency is a common approach used in shielding. The reader can think of waveguide penetrations for fiber optic lines and honeycomb-like vents for shielded room ventilation. Of course, the ideal approach will be to make the cross section of the passage as small as possible to have the cut-off frequency as high as possible. It must be recalled that personnel must be able to walk through this tunnel comfortably. Additionally, absorber will be lining the walls and ceiling of this tunnel. The floor may also have absorber under a subfloor. The author does not recommend the floor absorber as it limits the weight that can be moved through the tunnel.

In addition to these there may be local laws that require certain clearance for the passage.
A cross-section of a tunnel is shown in figure 4. The dominant mode is shown superimposed. There will be a cut-off for horizontal polarized fields and a cut-off for vertically polarized fields. The cut-off frequency is given by

\[ f_{c01} = \frac{1}{2a\sqrt{\varepsilon_\mu_d}} \]  

(1)

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 of passage. For the tunnel shown the vertical field cut-off is 86.79 MHz, while for the horizontal case the cut-off is at 61.47 MHz. For these calculations the absorber is ignored. Table II shows the attenuation that can be achieved for a 4ft section without the absorber lining the structure, just by looking at the losses on the steel walls.

![Figure 4. A cross section of a passage with absorber lining the ceiling and walls.](image)

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

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Vertical field Attenuation for 4ft (dB)</th>
<th>Horizontal field Attenuation for 4ft (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 40dB for a 16ft section. All this theoretical background was presented in [1]. However only part of the story is told. As mentioned above, to help the middle frequency range, absorber must be added to the walls and ceiling. Adding the absorber loads the waveguide and shifts down the cut-off frequency. This is something that is ignored in [1]. The new cut-off as given in [3] is

\[ \frac{1}{2a\sqrt{\varepsilon_\mu_d}} \leq f_c \leq \frac{1}{2a\sqrt{\varepsilon_\mu_d}} \]  

(2)

Equation (2) shows that the cutoff is between the cutoff of a waveguide filled with 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. This approach was presented in [4] to estimate the attenuation in an absorber pyramid. A typical 12-inch (30cm) pyramidal loaded polyurethane foam has an \( \varepsilon_r \) of about 30 at 60MHz. The wavelength inside the foam are about 5.4 times shorter. Thus the tunnel appears about 18 inches (45cm) taller and 36 inches (90cm) wider at 60MHz. This shifts the cutoff frequency for the horizontal case down to 51.7MHz. As reported in [5], longer absorber has a lower permittivity but using longer absorber means that the cross section of the passage has to be larger to accommodate the absorber and leave clearance for people to use the tunnel. The larger cross section pushes the cut-off frequency further down and makes it more difficult to achieve attenuation above cut-off.

Mid-range frequencies are the most difficult to attenuate. A typical passage will have a cross section of about 8 ft (2.44 m) or 8 ft (2.44 m) by 6 ft (1.82 m) to allow for easy access of equipment such as carts or racks of equipment on casters, and personnel. For some facilities, the requirements of other standards have to be met. EMC and RF engineers may not think of these guidelines and government mandates, such as those in reference [6] that regulate the minimum clearance for wheelchair access. For example, [6] requires a 60 inch clearance from wall to wall for a corridor where two wheelchairs may cross each other. Different countries have different guidelines, the ones on [6] are used here to illustrate the point.

Based on this, let’s assume that the tunnel will be 8 ft (2.44 m) by 8 ft (2.44 m) in cross section. From equations (1) and (2), the cutoff is calculated to be at about 61MHz. The walls and ceiling of the corridor will be lined with 12-inch absorber. The floor is not lined to have a more solid surface for motorized wheelchairs to access the shielded area. It is true that there are floating floors that can handle heavy loads, but the material is so reflective that placing absorber under it does not help in attenuating the waves. The tunnel has enough clearance to meet the requirements of reference [6]. A simulation is performed on a 14ft section of the passage. The shielding effectiveness shown in figure 5 is obtained.

![Figure 5. Shielding attenuation of a straight section of passage lined with 12-inch pyramidal absorber.](image)
Care must be taken in interpreting the results shown in figure 5. Between 50 and 70MHz the coupling between the antennas is higher than it was in the reference. This yields a shielding level higher than 0dB. 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 in transmitting more power to the receive antenna. The data do show the difficulty of getting a good shielding effectiveness with these passages between 30 and 100 MHz. Using turns will be required to achieve any usable level of shielding at those frequencies.

Another option is to use a hybrid absorber. Hybrid absorbers that use a carbon loaded foam over a ferrite tile are very common in EMC applications. These absorbers have limitations at higher frequencies as they use of a foam with a lower carbon content to better match the ferrite [7]. Typical profile of the ferrite tile is only 6 mm. A simulation is performed with tile 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. This approach is commonly used in automotive EMC chambers.

Figure 6 shows the performance of such a straight section of tunnel lined with an 8-inch tall truncated pyramid over ferrite tile (that makes up the hybrid absorber) and ferrite tile on the floor.

![Figure 6](image)

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 80MHz.

The data in figure 6 shows that the use of the hybrid absorber provides much higher numbers of attenuation than what the standard absorber does. Notice, however, that as the frequency increases, the effectiveness of the straight section is reduced. Turns will provide the desired levels at higher frequencies into the microwave range.

IV. ANALYSIS OF Turns

The high frequency attenuation depends on the turns. This is because the absorber that lines the back wall of each turn will provide the attenuation. 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. That longest absorber will also contribute to attenuating the mid-range, which, as shown above, is limited in the straight section of the passage. Using the longest material, however, may not be necessary, and it is 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 biconical antennas in free space, as shown on 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 perfect electric conductor (PEC) was placed between the antennas to cut any direct coupling between them. The only path for the energy to transmit from one to the other is through the turn. Figure 7, shows the model created for such simulation the “roof” of the tunnel and the ceiling absorber have been hidden for clarity. In figure 8, the field distribution is shown for the two principal polarizations at three different frequencies.

![Figure 7](image)

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.

As stated above, it could be tempting to use the largest possible absorber. However, the simulations done for typical absorber 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.

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 100MHz. while the use of 6ft pyramids requires 48 sq. ft. of extra space to be implemented at every turn.
Now all the pieces of the tunnel, have been analyzed. The low frequency attenuation provided by the cut-off. The attenuation of straight sections lined with hybrid absorber. The attenuation at 180 degree turns. The performance of each section can be cascaded to design an access passage with a given level of attenuation or shielding effectiveness.

Let us, verify that cascading is acceptable. To do so, a simulation is performed of a double turn. Comparing the results for a single turn with 12-inch absorber presented in figure 9 to the results for a double turn shown in figure 11, it can be seen, that the performance has significantly improved. At 100MHz, the computed SE went from 14dB at 100MHz for the vertical polarization for the single turn, to 27dB at 100MHz 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. These results support the idea of cascading the performance of the sections of tunnel.

Figure 12 shows the plan view of a tunnel. The tunnel has two straight sections treated with hybrid absorber and ferrite tile on the floor. A total of four turns with 24-inch material on the back wall of the turn provide the attenuation at frequencies above 100MHz.

The design proposed is intended to give the best possible performance while meeting certain requirements for clearance and ability to bring heavy loads into the shielded area. Table III shows the expected levels based on the different simulations performed.

<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 100MHz mark is a difficult range to achieve SE numbers in the 100dB level. Even as we approach the cut-off frequency from below, Evanescent waves can propagate with attenuation. And if the tunnel is not long enough, then the SE will be compromised. If the critical frequencies where the work is being performed inside the shielded enclosure are above 1GHz, these passages are economically feasible as an entrance to the shielded enclosure.

I. CONCLUSIONS

While tunnels 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 has a use for access to people with disabilities and also for moving heavy loads, such as racks of equipment, since there are no high thresholds on the path.
II. CONCLUSIONS

While tunnels 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 has a use for access to people with disabilities and also for moving heavy loads, such as racks of equipment, since there are no high thresholds on the path.

Shielded tunnels are very rarely going to exceed the performance of shielded doors unless an extremely large area is reserved for their implementation. 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.

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

![Figure 11](image1.png)

**Figure 11.** Results for the simulation of a double turn with 12-inch pyramidal absorber on the receive end walls.

![Figure 12](image2.png)

**Figure 12.** A recommended shielded door-less access for a large shielded enclosure.

REFERENCES


BIOGRAPHICAL SKETCH

Vince Rodriguez attended The University of Mississippi (Ole Miss), in Oxford, Mississippi, where he obtained his B.S.E.E., M.S. and Ph.D. in 1994, 1996 and 1999 respectively. He was a visiting professor at the Department of Electrical Engineering at Texas A&M University-Kingsville, from 1999 to 2000. Dr. Rodriguez worked at ETS-Lindgren from 2000 to 2014. During this time he designed E field generators, anechoic chambers of different types including rectangular and taper antenna. Dr. Rodriguez was in charge of the development of new antennas. Among the antennas developed by Dr. Rodriguez there are: broadband double and quad-ridged guide horns; high field generator horns; stacked LPDAs for automotive and military testing; and printed antennas for wireless testing. His 2005 AMTA paper introduced the Open Boundary Quad-Ridged Horn type antenna. Dr. Rodriguez joined MI Technologies (Now NSI-MI) in Suwanee, GA in 2014 as a Senior Applications Engineer concentrating on Antenna, RCS and radome testing facility design. He is now a Staff Engineer at NSI-MI’s Applications and Systems Engineering group. His Job consists in quantifying customer needs and proposing solutions to these needs. As part of the group he is also responsible for advancing the measurement techniques related to antenna, radome and RCS.

Dr. Rodriguez is the author of more than fifty publications including journal and conference papers as well as book chapters. He holds two patents for hybrid absorber and dual ridge horn antenna. He is a Senior Member of the IEEE and several of its technical societies. He is a member of the EMC Society, where he is serving as Distinguished Lecturer of the society from 2013 to 2015 and the board of directors of the society. He is an Edmund S. Gillespie Fellow of the Antenna Measurements Techniques Association (AMTA). He has served as AMTA meeting coordinator (2010-2011) and as vice president for the year 2012. He has served as a reviewer for the ACES Journal and for the Journal of Electromagnetic Waves and Applications (JEW). He has served as chair of sessions at several conferences of the IEEE, AMTA, CPEM (conference on precision electromagnetic measurements). He served in the RTCA DO-213 standard (weather radar radomes measurements) working group. He is currently a member of the working group for the IEEE Std. 1128 (RF Absorber Measurements) and the IEEE Std. 149 (Antenna Measurements) working group where he serves as secretary.