EXPLORING THE POTENTIAL HIGH ENERGY LOCATIONS AND INTENSITIES IN CONFINED WORK SPACES OF WAVEGUIDE DIMENSIONS

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Abstract: Adequately identifying and managing hazards at the workplace can be a tedious task which extends into the realm of uncertainty, probability and prediction models in order to fully comprehend the nature of the hazard. As such, organizations cannot be blamed for knowledge gaps in the training of personnel they contract to ensure a safe and healthy work environment, especially where there are latent hazards. Electromagnetic wave propagation at frequencies in the SAR (specific absorption rate) region is a special concern to authorities involved in setting RF (radiofrequency) and microwave exposure guidelines. Despite that there is no conclusive evidence to suggest that non-ionizing electromagnetic radiation causes adverse health effects other than thermal, no effort should be lost to ensure that workers and the public at large are adequately protected from unnecessary exposure to radiation. Standards however set exposure limits for free space, plane wave propagation but fall short in compiling information on intensities of these waves after they undergo reflection and diffraction from wall surfaces. Waveguide technology has managed to constrain microwaves to remain within set boundaries, with fixed frequencies that force the waves to behave differently to if they were moving in free space. This technology has offered the ability to transport more energy for communication purposes other than transmission lines. The size of a waveguide may be to the order of a few centimetres and can guide RF of wavelengths of the order of centimetres also but what if spaces of larger dimensions are capable of being waveguides and can guide waves of larger wavelengths such as those that correspond to frequencies between 30MHz to 300MHz? Such RF waves belong to the SAR region of the spectrum where strict exposure limits are set for health and safety protection since a standing man acts as a dipole antenna for this radiation and can absorb maximum energy from propagating RF waves. This review visits the likelihood for potential energy build-up due to RF propagation in confined spaces that are of waveguide design but with larger dimensions. Such confined spaces include silos, tanks, pipes, manholes, air-condition ducts, tunnels, wells, engine rooms and operator rooms on board vessels. In these confined spaces waves reflect off of the walls and combine constructively or destructively with incident waves producing reinforcement or cancellation respectively. Where there is reinforcement, the intensity of the wave for a particular distance in accordance with the standard, may exceed the exposure limit for this distance from the source thereby exposing the...
worker to larger intensities than the accepted limit and presenting a potential health and safety threat.

**Keywords:** RF hazard, SAR, confined space, reflection, waveguide

1. **Introduction**

   In the past, workers in organizations were expected to complete their tasks in sub-standard conditions within a given time frame which contributed to worker health and safety issues. Of special interest to worker safety is work performed in confined spaces. A confined space is one which has limited access and egress and accommodates one employee or two to perform some work function that may take a period of time unsuitable to the health and safety of the employees exposed. Such spaces include: tanks, a/c ducts, storage bins, pits, vessels, silos, and man-holes. (NCDOL, 2012).

   Confined spaces pose potential threats that are not readily visible, (latent hazards), to the health and safety of workers and may lead to fatal injuries because there is failure to recognise and treat the hazard and the suitability of the emergency response (NCDOL, 2012). These spaces may accumulate gases and toxic fumes, poor lighting, and may be a hub for harnessing electromagnetic fields. RF fields can be generated by propagating electromagnetic waves in the SAR region of the spectrum (30MHz to 1000 MHz) and can be a potential hazard to a standing man. International standards set stringent exposure limits for RF in this frequency range, siting restrictive measures of monitoring, maintenance and reporting for sites using equipment within this range (IEEE C 95.1 1999). The OSHA of the United States has set a maximum exposure level of 10 mW/cm² for frequencies between 10 MHz and 100 GHz averaged over a 6 minute period, while IEEE sets at 1mW/cm² and E (electric) field at 61.4 V/m over the same period.

2. **Exposure Standards**

   International exposure limits are set for thermal effects and possible electro-stimulation, shocks and burns for controlled and uncontrolled environments. Standards are however not fault proof and may from time to time not fully address all the risks to the hazard present since hazards may change depending on their location, presence with other hazards or other perilous conditions and interaction with artefacts. The standards therefore give a probability of safety but do not guarantee it, which should prompt safety practitioners to engage in methods of determination and analysis of the risks posed by hazards in a more inclusive and holistic manner. (IEEE C95.1 1999).

   There has been public concern that electromagnetic waves coming from the various sources cause persons to have headaches, develop rashes, cancer, nervous disorders, irritability, moodiness, breathing difficulties, muscle pain, mental depression, among other claims (Cember, 1996). While the thermal effects have been substantiated there is no conclusive evidence of non-thermal effects despite the findings and reviews from many scientists and researchers who claim that there are adverse health effects. To balance the claims, a neutral position is taken in the IEEE C 95.1 standard with strict limits set at 30 MHz to 300 MHz where the SAR (specific absorption rate) region is most dangerous to a standing man. (Rodriguez 2008).

   The standards set guidelines generally for RF propagation in free space for plane waves. It is difficult to accept that RF exposure in free space is the same as that within a confined space where the energy is confined within boundaries. The standards have not strictly focussed on RF propagation in the 30 – 1000 MHz region or SAR region, inside of rectangular and cylindrical life-size structures likened to communication waveguides for microwave propagation. According to IEEE, a RF hot spot is a highly localized area of relatively more intense radio-frequency radiation that manifests itself in
localized areas in which there exists a concentration of radio-frequency fields caused by reflections and/or narrow beams from antennae.

There are three major concerns then, up for consideration at this point if we are to address this RF propagation in confined spaces:

i. whether there is any difference between RF propagation in free space (unbounded) as opposed to confined space (bounded) propagation;

ii. can we use waveguide theory to treat smaller frequencies (longer wavelengths) of RF propagation in large structures (confined spaces) in the same way we do with the larger frequencies (smaller wavelengths); and

iii. whether or not there are high energy points (RF hot spots) inside confined spaces where waves reflect and interfere constructively.

The modelling of wave propagation is essentially for the determination of the probability of accepted performance for communication systems and is a major factor when planning network systems. There are a variety of models to suit applications of which many do not suit the applications they were designed for and as such there is much room for RF propagation modelling. In this regard, RF modelling has its genesis in statistics as we try to determine the location and intensity in the environment in which it is contained. In the words of Seybold, ‘the selection of a model to be used for a particular application often turns out to be as much art (or religion) as it is science’. (Seybold, 2005). Between 30 MHz and 1GHz for RF waves, we can expect refraction and reflection as dominant factors but as the frequency increases, the skin effect produces more attenuation which is readily observed at microwave frequencies (Seybold, 2005). This is in support for the methodology proposed here in this article for RF hot spots, since reflections of RF in the frequency range 30 MHz to 1000 MHz (below microwave frequencies) off of the inner walls of rectangular confined spaces are under consideration.

When electromagnetic radiation strikes a surface some of the radiation reflects off the surface while some is transmitted through the medium it strikes. The amount of radiation reflected is dependent on the coefficient reflection of the material or reflectance, i.e. the ratio of the reflected to the incident flux. For high reflectance materials or specular reflection, we expect maximum reflection with small transmission and the angle of reflection to be equal to the angle of incidence. (Hecht 1975).

3. Waveguides
RF energy can be transmitted via transmission lines, antennae or waveguides as sources to receiver antennae. Waveguides are usually small with dimensions just larger than that of the wavelength of the wave travelling along it; these may be about ‘a’ = 6 cm x ‘b’ = 3 cm in rectangular cross sectional area, see Fig 1.

![Waveguide Diagram](http://en.wikipedia.org/wiki/File:Waveguide.svg)

**Fig 1.** Picture of typical waveguide [Source: http://en.wikipedia.org/wiki/File:Waveguide.svg]
Table 1 shows typical waveguide dimensions for microwaves. The last column, column 6, shows the inner dimensions of width and height and it can be observed that the ratio is 2:1. For this condition, propagation of waves can exist without much loss in energy. For such dimensions there can be a number of possible modes by which energy can be transferred with each being characterized by a distinctive field configuration.

An electromagnetic field can propagate along a waveguide in various ways. Two common modes of propagation are known as transverse-magnetic (TM) and transverse-electric (TE). In TM mode, the magnetic lines of flux are perpendicular to the axis of the waveguide.

In TE mode, the electric lines of flux are perpendicular to the axis of the waveguide. Either mode can provide low loss and high efficiency as long as the interior of the waveguide is kept clean and dry. (Bhattacharya et al, 1999).

To function properly, a waveguide must have a certain minimum diameter relative to the wavelength of the signal. If the waveguide is too narrow or the frequency is too low (the wavelength is too long), the electromagnetic fields cannot propagate. At any frequency above the cut-off (the lowest frequency at which the waveguide is large enough), the feed line will work well, although certain operating characteristics vary depending on the number of wavelengths in the cross section. Guided waves are used where high efficiency is required and despite losses that occur which are not normally found with free space waves, these are offset since the waves are no longer divergent as an expanding ball but confined to a rigid path of fixed cross-section (Mathews and Stephenson, 1968).

Waves of frequencies between 20 – 3000 MHz are used for line of sight communications in aircrafts, FM, TV and amateur radio broadcasting and contain wavelengths comparable to the dimensions of large trees and buildings which provide good reflecting surfaces. Communication can be cancelled or enhanced depending on whether there is destructive or constructive interference between direct and reflected radiation. (Whitaker 2002).

4. Confined space philosophy

Buildings, houses, vehicles, tanks, silos are just some of the everyday structures we design for ourselves that in fact may perform the same function as a waveguide used in communication for the efficient propagation of microwaves.

The formulae for wave propagation inside a rectangular wave guide are as shown:

Table 1: Standard sizes of waveguides

| Waveguide name | Frequency band name | Recommended frequency band of operation (GHz) | Cutoff frequency of lowest order mode (GHz) | Cutoff frequency of next mode (GHz) | Inner dimensions of waveguide opening (inch) |
|----------------|---------------------|---------------------------------------------|--------------------------------------------|-------------------------------------|-------------------------------------------|
| WR2300 WG0.0   | R3                  | 0.32 — 0.45                                | 0.257                                      | 0.513                               | 23.000 × 11.500                          |
| WR2100 WG0     | R4                  | 0.35 — 0.50                                | 0.281                                      | 0.562                               | 21.000 × 10.500                          |
| WR1800 WG1     | R5                  | 0.45 — 0.63                                | 0.328                                      | 0.656                               | 18.000 × 9.000                           |
| WR1500 WG2     | R6                  | 0.50 — 0.75                                | 0.393                                      | 0.787                               | 15.000 × 7.500                           |
| WR1150 WG3     | R8                  | 0.63 — 0.97                                | 0.513                                      | 1.026                               | 11.500 × 5.750                           |

[Source: http://www.bing.com/search?q=table+of+standard+waveguide+sizes&form=MSNH14&refig=99af3dee9e594fd3af12565b4683d5b2&pq=table+of+standard+waveguide+sizes&sc=0-3&sp=-1&qs=n&sk=]
1. \( c = 3 \times 10^8 \text{ m/s} \) (c= speed of light in vacuum)

2. \( \lambda_{mn} = 2 / \sqrt{((m/a)^2 + (n/b)^2)} \)\): (cut-off wavelength for m, n modes for m=1,2,3…, n = 0,1,2,3..)

3. \( \sin \theta = \lambda/c \)\: (angle of incidence at entrance of guide)

4. \( f_{cmn} = c/2 \sqrt{((m/a)^2 + (n/b)^2)} \)\: (cut-off frequency for m, n modes)

Source: [http://www.ece.msstate.edu/~donohoe/ece3323waveguides.pdf](http://www.ece.msstate.edu/~donohoe/ece3323waveguides.pdf)

For any wave propagating down a wave guide, it does so in the Z direction with a group velocity given by \( U_g \). In so doing, a stationary wave pattern is set up as the waves bounce off of the walls of the guide in a ‘zig-zag’ manner in the XZ plane with velocity in direction of wave travel, \( U_u \).

There is therefore a component of wave motion in both Z and X directions. The Y direction addresses the oscillations of the electric field E only and there is no wave motion there just as there is no component of E in either Z or X directions. The E field spreads across the width of the guide and is half wavelength of the propagating RF for the TE10 mode with maximum field strength at the centre and falls off to zero at the walls. For the TE20 mode, the width is two \( 1/2 \) wavelengths and the E field distribution is \( E^+ \) and \( E^- \) across the width corresponding to maxima at top and bottom.

http://www.ece.msstate.edu/~donohoe/ece3323waveguides.pdf

5. Sample Scenario (Fig 2)

Consider that a rectangular high reflectance air-condition duct of width \( a = 1.75 \text{m} \) and height \( b = 0.88 \text{m} \) is in the line of sight of a RF broadcasting antenna. The incident plane waves emanating from the antenna strike the open rectangular duct (waveguide) at 60 degrees to the Z axis of the duct. Determine which frequencies can propagate through this duct if the space is to operate as a waveguide for the TE10 mode in single mode operation.

Single mode operation occurs when the guide allows only one frequency within the dominant mode to propagate, in this case it is 98.9 MHz. Recall the cut-off frequency \( f_{cmn} = c/2 \sqrt{((m/a)^2 + (n/b)^2)} \); m=1 n=0 for TE10 mode which is 85.7 MHz for this guide dimension. For width \( a = 1.75 \text{m} \) and angle of incidence 60°, then \( f = f_c / \sin 60 \) which is equal to 98.9 MHz. If the antenna emits at 98.9 MHz, then since this frequency is higher than the cut-off, it should be able to propagate down the guide, air-condition duct in this case, once excited. For guide operating as a single mode operation, i.e., for the TE10 mode only, waves with frequency 98.9 MHz that strike the entrance at 60° will propagate and fill up between the points A to Z. Incident waves strike the wall of the duct at Z and G and at 30° to the normal (n) at the wall’s surface and reflect at the same angle 30° and continue to E and F. These will then reflect from this surface to strike the first surface at H and L, see Fig.2.

Interference occurs within triangles: OZG, OEF and OHL where incident and reflected rays cross. These are considered potential RF hot spots and the triangles that house them are hot zones. The hot zones are all of same area and repeat periodically and give the probability of RF hot spots, where the waves interfere constructively. These hot spots will have higher field intensities than the waves that do not interfere constructively and are therefore potential spots of higher exposure.

The field intensity for an incoming wave is \( E_i = E_0 e^{j\omega t} e^{-\gamma z} \)\: (unbounded) where \( \gamma = \alpha + j\beta \) and \( \gamma \) is imaginary if (attenuation factor) \( \alpha = 0 \). i.e. there is no attenuation of the wave. Inside the confined space the wave equation becomes: \( E = E_0 e^{j(\omega t - \beta z)} \)\: (bounded) for the time varying wave propagation in the z direction and the stationary wave set up in the x direction, where \( \omega \) is the frequency of the wave, \( \varepsilon \) is the phase change upon reflection, \( \beta \) is the phase constant of the wave, \( E_i \), \( E_0 \), \( E_r \) are the incident, initial and reflected electric field intensities.

The reflected wave is \( E_r = E_0 e^{j(\omega t + \varepsilon - \beta z)} \)\: (bounded). For constructive interference, \( E = E_i + E_r \). The area of each triangle by geometry is the same. For triangle OZG then, the area is: \( 1/2 \) (ZG) \( (a/2) \), which is \( a/4 \) ZG.
ZG = AE = EF = HL, \( a/ ZG = \tan \Theta = \tan 60 \). So \( ZG = a/ \tan 60 = 1.01 \) units. Area of triangle is therefore: \( (a^2/4) \tan 60 \), i.e., \( (1.75^2/4) \tan 60 = 0.44 \) units\(^2\). It is within this confined area we can expect RF hot spots to exist. [http://www.ece.msstate.edu/~donohoe/ece3323waveguides.pdf](http://www.ece.msstate.edu/~donohoe/ece3323waveguides.pdf)

### Table 2: Cut-off frequencies in TE10 mode for varying rectangular confined space widths ‘a’ in Single Mode Operation

| Confined space name | a/ m | b/ m | \( f_c/ \) MHz | Single mode freq. at 60°/MHz | SAR |
|---------------------|------|------|----------------|-----------------------------|-----|
| CS200               | 2.00 | 1.10 | 75            | 86.6                       | Yes |
| CS175               | 1.75 | 1.40 | 85.7          | 98.9                       | Yes |
| CS150               | 1.50 | 0.75 | 100           | 115.5                      | Yes |
| CS125               | 1.25 | 0.65 | 120           | 138.5                      | Yes |

If the angle of incidence of the waves at the guide entrance is smaller, then larger frequency waves will propagate and those below will not. If we are trying to stop the FM band between 86.1 and 107.1 MHz for example, then ‘a’ can be varied to achieve this. Table 2 gives some widths and corresponding cut-off frequencies for the TE10 mode. Table 2 unlike Table 1 addresses the larger guide dimensions and has been constructed in this presentation as an equivalent informative chart using the layout prescribed in Table 1. The Table will therefore assist in being a first observation point for knowing what frequencies will propagate in our design of a confined space and whether they are within the SAR region. These are the frequencies to be weary of since constructive interference within the confined space could lead to RF build-up and hence RF hot spots.

**Fig 2:** Confined space of width ‘a’, as a single mode operation waveguide for cut-off frequency in TE10

### 6. Conclusion

This article presents a thought – provoking notion of large waves in SAR region propagating down rectangular confined spaces just as microwaves would in waveguides setting up standing waves due to interference of incident and reflected waves within the space. These RF hot spots possess the potential to contain higher field intensities than if the waves were propagating in free space. When we therefore consider safety hazards due to noise, lighting, toxic and gas build-up within confined spaces, accumulation of RF along the confined space must also be given consideration.
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