Reconciling the criteria that determine exposure to electromagnetic fields

Following the various Guidelines that have been issued by Ofcom, as well as using the on-line calculators provided both by Ofcom and the RSGB, has proved to be an interesting (though not terribly rewarding) exercise. It is clear that they are still finding their way in what is a far from settled world of standards devised by the two major international bodies: ICNIRP across Europe, with Ofcom as the implementing authority in the UK; and the IEEE in the USA where the FCC determines the legislation. Given the differences that exist between them it is perhaps no surprise that the 'average' radio amateur is somewhat bemused by it all.

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The latest publication by the ARRL on this subject (in QST of September 2021), "Understanding the changes to the FCC RF exposure rules" written by Ed Hare W1RFI, the author of the ARRL publication "RF Exposure and You", (1998 – 2003), sets out to clarify some of these issues. http://www.arrl.org/files/file/QST/This%20Month%20in%20QST/2021/09%20September%202021/HARE.pdf However, the numbers that appear in its various tables are still unexplained. I therefore tried to reconcile at least some of them with the underlying theory.

There are two important tables in that article. They set out the various criteria that apply across the RF spectrum in order for amateur radio (and other) stations falling under the jurisdiction of the FCC to comply with its EMF Guidelines. They also form the basis of my analysis which follows and I will refer to both tables frequently. So as not to cause any confusion with the QST tables my truncated versions will be called **Table A** and **Table B**. As will be seen below, **Table A** gives the limiting values for the electric (E) and magnetic (H) fields, as well as the power density (S) where it is applicable. The original FCC table is divided between the two categories of Occupational/Controlled Exposure and General Population/Uncontrolled Exposure. Only the second of those is of interest to radio amateurs, their immediate neighbours and passers-by. So only it is shown below.

Table A. 'Limits for Maximum Permissible Exposure (MPE):

General Population/Uncontrolled Exposure'

$Frequency\ Range\ (MHz))$	$E\ (V/m)$	$H\ (A/m)$	$S\ (mW/cm^2)$
0.3 – 1.34	614	1.63	(100)
1.34 - 30	824/f	2.19/f	$(180/f^2)$
30 - 300	27.5	0.073	0.2
300 - 1500			f/1500
1500 - 100000			1

Values in parentheses are 'plane-wave equivalent power density

The magnitude of the units used in the power density column S are unusual. In the SI system, it is more common to use W/m^2 than the mW/cm^2 quoted in the QST table. For every mW/cm^2 there are ten W/m^2 simply because of the change of units. The actual power density is unaltered. I shall use $S = \frac{1800}{f^2} W/m^2$ in what follows. This is also the approach followed by ICNIRP and, intriguingly, by the IEEE which produced the Guidelines followed by the FCC in the USA.

People as antennas

It will be noted that across the HF band (1.34 and 30 MHz as chosen by the FCC) that both the E and H field expressions, as well as the power density S, are frequency-dependent within that range whereas they are constant it and again across the VHF band with frequency dependency evident at UHF and constant again in the microwave region. Why should this be? The reason is to be found in the significant differences between the applicable magnitudes of E, H and S allowed both below and above HF. At the sub-HF end the tolerable magnitudes are considerably greater than they are at VHF. It is therefore necessary for there to be a transition between them and that is the reason for the frequency dependence of all three quantities between 1.34 and 30 MHz. The underlying physical reason is that an erect human being acts as an antenna, albeit a rather lossy one, and so would respond differently at different frequencies. Taking that aspect one step further, it is not at all surprising that such a person would actually resonate at some frequency based on the individual's height and the electrical characteristics of the ground beneath their feet. To cater for adults and children, whether standing erect or in any other position, there is a wide range of frequencies within which resonance may occur. The various guidelines allow for this by setting the tightest restrictions (i.e., the lowest values of E, H and S) between 30 and 300 MHz.

The fourth column in **Table** A is extremely important because it is where the FCC/ARRL approach parts company with that being followed by Ofcom/RSGB**.**

The Ofcom and RSGB calculators

Table A specifies the limiting values of the power density across the complete frequency range from 300 kHz to 100 GHz. In a footnote we are informed that the parentheses imply that S is 'plane-wave equivalent power density' at those frequencies but there is no explanation within the rest of the article (nor in the formal FCC guidelines) as to what that actually means. By contrast, the prevailing situation within ICNIRP/Ofcom/RSGB is very confused. In their 1998 Guidelines ICNIRP decreed that all frequencies above 10 MHz lie within the far-field region within which the concept of power density is valid and hence is applicable. However, ICNIRP's 2020 guidelines mark the incident power density as being NA (not applicable) at all frequencies below 30 MHz, thereby effectively placing the complete HF spectrum within the near-field (NF) zone of the radiating antenna. Despite this Ofcom and the RSGB are apparently ploughing on with their calculators which make use of mathematical relationships which are only valid within the far-field – hence their use is restricted to frequencies above 10 MHz at the moment. What will happen when we all have to comply with ICNIRP 2020 has not been revealed.

Those calculators are based on a mathematical expression first published by Harald Friis of the Bell Telephone Laboratories in New Jersey in the 1940s. It applies only in the far-field and defines the power density S, at some distant point R for a given amount of radiated power. The Friis equation is independent of frequency. However, a glance at the **Table A** shows that the limiting field strengths and power densities, in some cases but not all, are (as noted above) very much frequency-dependent and so the equation required modification, both by the IEE/FCC, and by ICNIRP/Ofcom, to take this frequency dependency into account. In addition, it was modified further to include the effect of ground reflections. All this will be discussed below.

The American approach

The FCC and the ARRL have avoided this near-field/far-field (NF/FF) problem by using those 'plane-wave equivalent power densities' at frequencies below 30 MHz and so, effectively, they treat the whole HF band as being within an 'equivalent far-field' zone. ICNIRP has not seen its way clear to doing that. My adapted version of the QST Table 1 is shown below. It should also be noted that the period of exposure, defined as the 'averaging time' during which these limits apply, is taken to be thirty minutes. There is also a six-minute period but, apparently, there is no agreement yet between the collaborating teams on opposite sides of the Atlantic as to which averaging period should apply.

<u>An important point to note on technical terminology</u>. The actual power radiated by an antenna is fundamental to this whole subject. It is given by G_tP_t where G_t is the gain of the antenna relative to some standard radiator and P_t is the average power fed into the antenna from the transmitter, which takes into account both the type of modulation and the duty cycles as well as any losses within the transmission line, its connectors and so on. For some reason, probably historical, the FCC, and hence the ARRL, have chosen to use the 'Effective Radiated Power' or ERP where the reference antenna is a half wave dipole in free space. Professional practice elsewhere has been to use the Equivalent Isotropic Radiated Power or EIRP where the reference is an isotropic source that radiates uniformly in all directions. There is a difference of roughly 1.64 times (or 2.15dB) between them. Thus EIRP = 1.64 ERP or, in decibels dBi = dBd + 2.15, where the subscripts i and d indicate whether EIRP or ERP applies. To avoid confusion, since I have used the information in that QST article as my starting point, I will use ERP unless otherwise indicated. This will be apparent in **Table B** below.

Table B. 'Single RF Sources Subject to Routine Environmental Evaluation under MPE-based Exemptions, $R \geq \lambda/2\pi$ '.

Transmitter Freq. (MHz)	Threshold ERP
0.3 – 1.34	1,920 R^2
1.34 - 30	3,450 R^2/f^2
30 - 300	3.83 R^2
300 - 1500	0.0128 R^2f
1500 - 100000	19.2 R^2

ERP is in watts, R is in metres and f is in MHz.

The so-called Threshold ERP within the specified frequency bands is given by various formulae all of which involve the distance R squared while some also include the frequency, with its reciprocal squared in one case and not in the other, as is apparent in **Table A**. Notice, too, that there is a general restriction on the distance R between the transmitting antenna and the specific point of interest at which the radiation intensity is being considered. R must be further from the antenna than $\lambda/2\pi$ or about a sixth of a wavelength. The reason for this will emerge in the discussion to follow.

Frequency-dependent restrictions

It will be seen that, between 1.34 and 30 MHz, the ERP is given by the expression $3.450\,R^2/f^2$. To illustrate its use in practice the QST article has two numerical examples. The interested user merely chooses some distance R appropriate to his particular situation (size of property, antenna height, etc) and then uses that expression to calculate the maximum ERP satisfying that specific case. This effectively turns the problem around; instead of calculating a distance one uses a selected value of R, determined by the size of one's property, and then finds the ERP which must not be exceeded in order to comply with the prevailing FCC EMF restrictions.

A couple of examples will demonstrate the use of the method.

<u>Example 1</u>. What is the maximum ERP allowed if the closest diagonal distance between the antenna on the top of its mast and the boundary fence is 10m when operating at 14.2 MHz using a Yagi with a gain of 8 dBi?

The wavelength is 300/14.2 = 21.1 m. Thus $\lambda/2\pi$ is 3.4 m. Clearly R = 10m, the distance between the antenna and the fence, is much greater than this so the calculation may proceed. The maximum or threshold ERP is then $3{,}450\,(10)^2/(14.2)^2 = \; 1711$ W.

The gain of the Yagi must be converted to dBd by subtracting 2.15 dB from its given value of 8 dBi . Hence G_t = 8 - 2.15 = 5.85 dBd which must be converted to a numerical value, as $10^{5.85/10}$= 3.85. The maximum permitted power, under 'key-down' conditions, is therefore $1711/3.85 = 445$ W.

<u>Example 2.</u> If the closest distance to the fence is only 7m then the allowable ERP, using the same method, is 838W. The maximum transmitter power will then be 218W when using that same antenna. Hence, to remain within the limits, the transmitter output power will have to be reduced accordingly.

This is all very well but where do these figures come from?

The defining equation

Table B shows the 'Threshold Effective Radiated Power (ERP)' across various frequency bands that make up pretty much the complete radio frequency spectrum. Immediately evident is that in every frequency range the ERP is a function of the distance-squared between the source and the 'target' individual who is to be protected. This is what is to be expected under certain conditions when the power density is not dependent on frequency but it is not the case in general. This will be evident from the defining equation (to be revealed below) that shows the part played by the frequency of the radiated signal. Unfortunately, none of this complexity was explained in the QST article nor was any information given as to the origin of the numerical coefficients which are now seen to play an important part in each of those frequency bands.

In the far-field region there is a particularly simple algebraic relationship between the power density S at any given point in free space and the effective radiated power by the source that gave rise to it. It defines (and explains) how the propagating electromagnetic wave, given by the Poynting vector $\boldsymbol{S} = \boldsymbol{E} \times \boldsymbol{H}$, is distributed in space. Thus

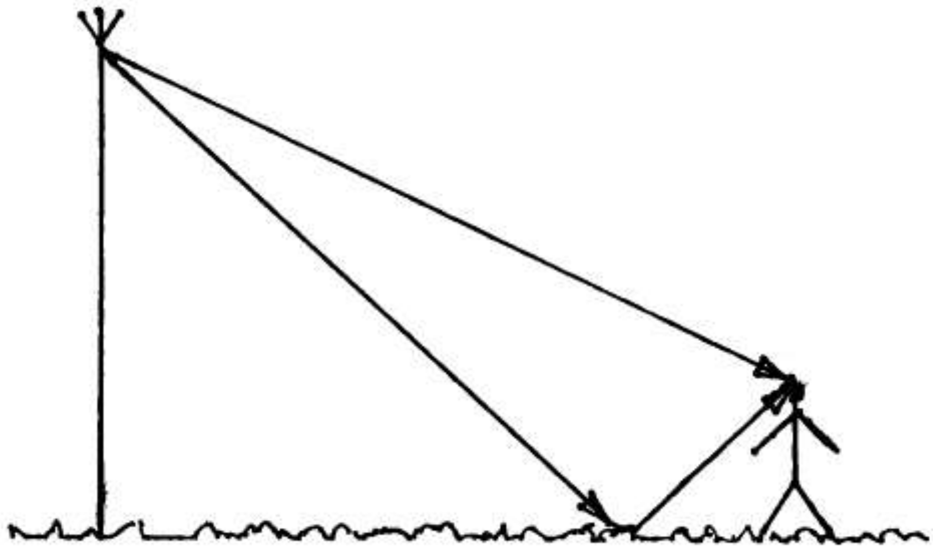
$$S = \frac{EIRP}{4\pi R^2}$$

EIRP = Gt Pt is the Equivalent Isotropic Radiated Power as explained above, while R is the radius of the mythical spherical surface, in space, that surrounds the antenna. This is the origin of the term isotropic which means ‘the same in all directions’. As mentioned above, there is a limitation to using this simple expression in that it only holds true when R is well within the far-field of the antenna. Both the IEEE/FCC and ICNIRP/Ofcom guidelines maintain that the boundary between the near and far fields (NF/FF) occurs at a distance of $\lambda/2\pi$ (or roughly a sixth of a wavelength) from the antenna, and they use this criterion to specify the limiting distance that has to be maintained under all circumstances in order to satisfy the compliance criteria. See **Table B** where this $R \geq \lambda/2\pi$ restriction is made clear. In reality, though, that NF/FF boundary is related to the dimensions of the radiating antenna. Only when they are very much less than a wavelength – i.e. the antenna is ‘electrically small’ - does this simple relationship of $\lambda/2\pi$ apply. For antennas larger than this, the NF/FF distance is usually taken to be $2D^2/\lambda$ where D is the largest dimension of the antenna. However, since the distance $\lambda/2\pi$ is apparently embedded within those Guidelines, I shall let it lie.

Modifying the equation

The power density equation above applies only in free space where there are no obstructions within the propagation path nor any reflections from other objects. In the real world the situation is rather different because the earth itself is a significant reflector and so this must be taken into account.

In both the FCC and Ofcom guidelines the power impinging on the person at a distance R is made up of both the direct ‘ray’ $E_d$from the antenna as well as that reflected E_r off the surface of the earth. The amount of reflection, indicated by a reflection coefficient $\Gamma = E_r/E_d$, is determined by, among other things, the electrical characteristics of the ground or sea from which the fields are being reflected. According to the International Telecommunication Union (ITU), $\Gamma = 0.6$ is representative of most practical situations. The part played by the reflected ray is illustrated in the diagram below.



The total field at R is then the sum of the direct and reflected rays which can be written as $E = E_d + E_r = E_d(1 + \Gamma)$. Now power density S is proportional to E^2, hence the term $(1 + \Gamma)^2$ must be included in the defining equations for power density. Thus

$$S = \frac{(1 + \Gamma)^2 EIRP}{4\pi R^2} = \frac{(1 + \Gamma)^2 (1.639) ERP}{4\pi R^2}$$

However, there is also the additional proviso that between 1.34 and 30 MHz and from 300 to 1500 MHz the relationships become frequency-dependent to allow for the resonance effects of the person exposed to the radiation.

In **Table B** the FCC expressed all this in terms of the ERP so, after rearranging, we find that

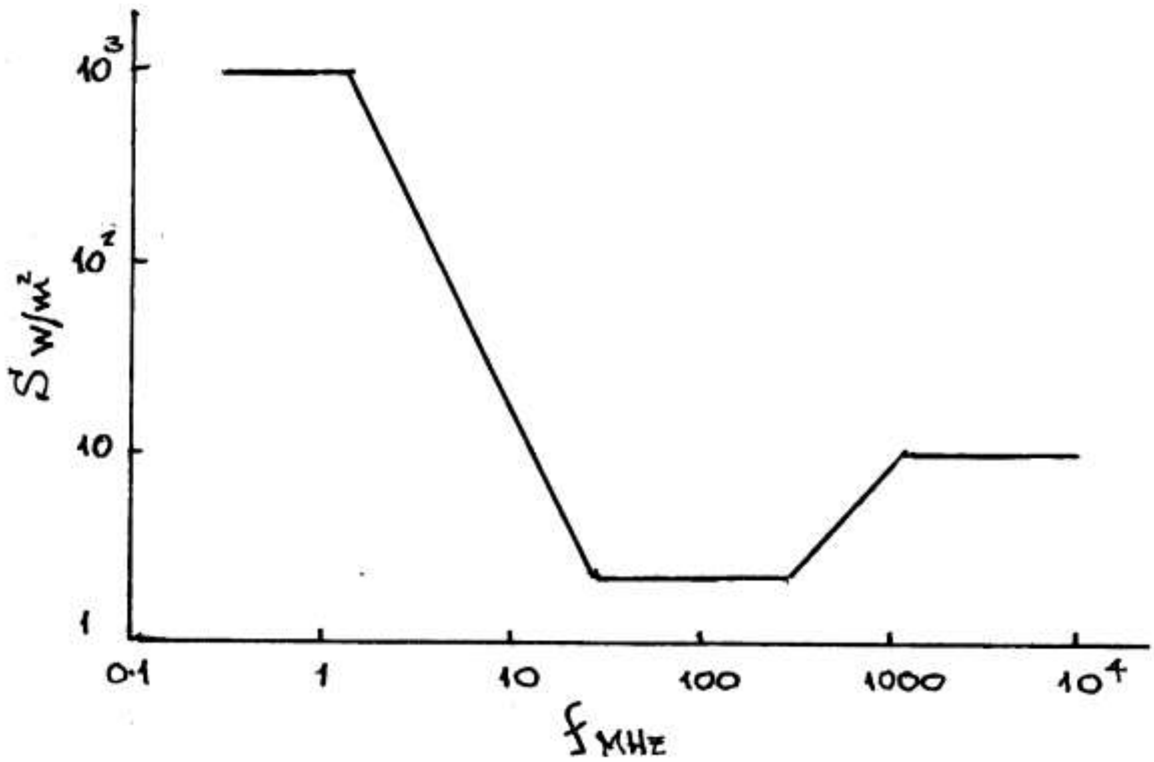
$$ERP = \frac{4\pi R^2 S}{(1 + \Gamma)^2 (1.639)}$$

These three equations, above, define the limits of the maximum permissible power density permitted and the resulting threshold ERP imposed by the FCC.

Massaging the numbers

If we consider the HF band between 1.34 and 30 MHz, and substitute this value of $\Gamma = 0.6$ into the equation for ERP, along with $S = 1800/f^2$ (from **Table A**), we find, to our surprise, that they do not yield the FCC coefficient 3,450 appearing in **Table B**. This is awkward to say the least! However, by working backwards from that value of 3.450 we discover that Γ turns out to be 1 and not 0.6. In other words, the FCC has assumed <u>total</u> reflection of the incident E field by the ground and this, naturally, maximises the resulting power density at the distant point R metres from the antenna. With hindsight we can see that the intention was to use this as the 'worst case' situation and so have some factor of safety to play with.

Given all the above, I have plotted in the graph below which shows the variation of power density against frequency but I have used the logarithms of both S and f in order to compress the large range of values involved and to linearise the expressions. The first thing to notice is that the resonance region described previously is clearly evident by the sharp decrease in allowable power density between 30 and 300 MHz. In addition, those regions where the power density is independent of frequency (between 0.3 and 1.34 MHz and above 1500 MHz) are shown.



This graph clearly represents the five regions designated by those various selected bands of frequencies as indicated by their corresponding ERP relationships in the two tables above. The negatively-sloping line between 1.34 and 30 MHz is of particular interest because it covers the HF band. Since it is a straight line, it can be represented by the equation $y = mx + c$ or, as here, as $logS = m\ logf + c$ where m is the (negative) slope, or gradient, of that line. The slope is given by the ratio of the appropriate vertical and horizontal axes on the graph occurring between those two frequencies, as follows.

$$m = \frac{log1000 - log2}{log1.34 - log30} = -2$$

This is what we would have expected since it represents the frequency-squared relationship within that HF region.

The constant c is found by solving the equation of that straight line $logS = c - mlogf$ which can be written as $c = logS + mlogf = logSf^m$. And, after taking antilogs, we have

$$Sf^m = 10^c$$

Since $c = log2 + 2log30 = 3.2553$, then $S = 10^{3.2553}/f^2 = \frac{1800}{f^2}$ which is now seen to yield the value used by the FCC and the ARRL to define the condition that applies across the HF band between 1.34 and 30 MHz. On substituting it, and $\Gamma = 1$, into the defining equation for ERP, derived above (but repeated here for convenience), we get

$$ERP = \frac{4\pi R^2 S}{(1+\Gamma)^2(1.639)} = 3450\, R^2/f^2$$

Clearly, this agrees with the expression for those frequencies shown in **Table B**. In addition, re-arranging the expression for S yields $S = 10^c/f^m$ and substituting for c and m, as determined above, yields S = 1000 W at 1.34 MHz and S = 2 W at 30 MHz, confirming the values of S below and above the HF band.

Some conclusions

The first thing to note is that the FCC/ARRL approach differs markedly from that presently being adopted by Ofcom and, thus, the RSGB. By using the concept of plane-wave equivalent power density the Americans are treating the full radio spectrum from 300 kHz to100 GHz in a consistent manner. They acknowledge that within the near-field of an antenna the simple far-field plane-wave relationships do not apply but by adopting this plane-wave equivalence method they enable relatively simple, yet adequately accurate, calculations to be made. They include the important proviso, also adopted by Ofcom and the RSGB, that minimum separation allowed between the antenna, and the point of interest R metres away, cannot be less than $\lambda/2\pi$. This FCC/ARRL approach is surely a sound way to tackle what could easily became a numerically intractable problem unless sophisticated antenna modelling software, beyond both the reach and the ken of most radio amateurs, is used.

By contrast, the situation in the UK is now hovering between two sets of ICNIRP guidelines – those of 1998 and 2020 - which, as far as the HF band is concerned, say very different things. Whereas frequencies above 10 MHz are treated, in the 1998 ICNIRP document as if far-field conditions apply, those below it are in limbo. But once Ofcom decides to enforce the 2020 ICNIRP strictures then all frequencies below 30 MHz will fall within the near-field and, as of now, neither Ofcom nor the RSGB has enlightened any of the ‘spectrum users’ (i.e., us) how we should go about ensuring that our radio installations comply with those Guidelines.

The American approach would seem to have much to commend it.

Brian Austin G0GSF (October 2021)