Abstract— More complex antennas with higher transmit power levels are being tested in compact range environments. AESA’s and other phased array antennas can transmit significant power levels from a relatively small volume. Without consideration of the impact of the transmitted power levels for a given test article, human and facility safety could be at risk. This paper addresses designing a test chamber in light of these power handling considerations for high power antennas on two fronts: 1) A methodology is presented to determine the power levels seen by surfaces in the chamber that are covered with absorber material and 2) Calculating the power levels seen at the compact range feed due to the focusing effect of the compact range itself. A test case is presented to show the application of the methods.

I. INTRODUCTION
Compact ranges are getting larger, allowing larger antennas. More and more active antennas are being tested in compact ranges and these antennas are becoming more powerful in smaller sizes. Given these trends, the range designer and user must start taking absorber power handling and human safety into consideration more and more. This paper will outline a straightforward set of calculations to determine if power handling issues will arise for a given antenna under test (AUT). These calculations fall into two categories: determining the power density impinging on absorber surfaces in the chamber and the power density at the compact range feed. For the remainder of this paper, the following test case will be used:

- Center fed single reflector compact range with a 3.66 m focal length.
- Chamber is 11 m long x 6 m wide x 6 m high.
- AUT is a 1 m circular aperture parabolic reflector with tapered illumination with efficiency ($\eta$) = 0.6.
- AUT transmit power = 500 W
- Operating frequency = 10 GHz

II. POWER LIMITATIONS

A. Absorber
Commercial pyramidal or wedge absorber is usually given a power handling specification in W/m$^2$. Most manufacturers offer “standard” absorber with power handling from 775 to 1500 W/m$^2$ [1] - [3]. “High Power” absorber is rated from 3100 – 3875 W/m$^2$ [1] – [3]. This rating assumes that forced air cooling of the absorber is not employed. It should be noted that the high power handling absorber is considerably more expensive than the standard absorber.

B. Human Exposure
Regulatory agencies define the allowable human exposure to RF energy in terms of power density versus frequency and time duration. The exposure limits are also divided into “controlled” and “general” categories. The controlled environment is one where workers are familiar with RF energy and its effects. Operators in an antenna test range fall into the controlled environment category. The Federal Communications Commission (FCC) limits are 6 minutes duration for 10 W/m$^2$ for frequencies from 30 MHz to 300 MHz, 50 W/m$^2$ for frequencies higher than 1.5 GHz and a linear transition from 300 MHz to 1.5 GHz [4]. The European standard is similar, only changing the 1.5 GHz breakpoint to 2 GHz [5].

III. CALCULATING POWER DENSITY ON ABSORBER SURFACES

A. Calculating Power Density at the AUT Aperture
The power density at the aperture is given by:

$$ P_D = \frac{P_t}{A_{eff}} \tag{1} $$

Where $P_t$ is the transmit power delivered to the aperture and $A_{eff}$ is the effective area of the aperture. For a uniformly illuminated aperture ($\eta$ = 1), the effective area is equal to the physical area of the aperture. With decreasing efficiency, the effective aperture shrinks and as noted by Kizer [6], the power density rises. For our test case, the physical area is 0.785 m$^2$ the effective area is 0.471 m$^2$, giving a power density of 1062 W/ m$^2$. Alternatively, if the gain of the antenna is known, the $A_{eff}$ can be calculated by:

$$ A_{eff} = \frac{G\lambda^2}{4\pi} \tag{2} $$

B. Calculating the Power Density Boundaries
The standard far field distance (beginning of the Fraunhofer region) is:

$$ R_{ff} = \frac{2d^2}{\lambda} \tag{3} $$

At this point, the power density is given by:

$$ P_D = \frac{P_tG_t}{4\pi R_{ff}^2} \tag{4} $$

Calculating power density with (4) at various $R_f$ is the Fraunhofer approximation for power density. Fig. 1 shows the
power density calculated with (2). The scaling of the plot is such that the X axis is the normalized range relative to \( R_0 \). The Y axis is normalized such that the power density is relative to the power density at \( R_0 \). The plot also shows the power density at the aperture for the given antenna. This plot shows that (2) would result in infinite power density at the aperture and obviously cannot exceed the power density at the aperture. Actual power densities at various \( R \) have to be confined to the lower left hand corner of the plot.

C. Calculating the Power Density in the Near-Field

It is well known that the power density within the near-field is oscillatory and work in calculating the near-field on axis power density for various apertures has proceeded since the original work of Bickmore and Hansen [7]. Peatross and Ware [8] present work from an optics perspective. Kizer [6] presents an extensive discussion of circular and rectangular apertures at various efficiencies. Paquay [9] and McKenna [10] are recent treatments of the circular aperture. Fig. 2 adds a Fresnel-Kirchhoff [8] approximation for a circular aperture of \( \eta = 0.6 \) to the boundaries in Fig. 1.

Note that the near-field power density peak occurs at one tenth the far field distance and then asymptotically approaches the Fraunhofer calculation.

D. Evaluating the Test Case

In I.A. above, the power density for the test antenna was calculated at 1016 W/m². At this point, any of the referenced calculation techniques for the Fresnel-Kirchhoff approximation can be used to calculate the power density at all \( R \) of interest. The result of the calculation for the test case is shown in Fig. 3. Note the following:

- The three horizontal lines are one absorber vendor’s high power absorber rating, the same vendor's standard absorber rating and the FCC human exposure limit.
- The vertical lines are, from left to right, the distances to the feed, side wall, back wall and reflector respectively.

The chart shows that the beam from the AUT is essentially collimated everywhere in the chamber. In addition a 500 W power from the AUT translates to a power density higher than standard absorber can handle. The solutions for this problem are to use the high power absorber everywhere in the chamber, reduce the CW power levels or use pulse techniques to reduce the average power seen by the absorber. Running at a 10% duty cycle gives the chart in Fig. 4. For the pulse approach, some consideration must be given to the risk of the pulse modulation system failing and the AUT transmitting at full 500 W power for any length of time. RF power sensor systems are available that detect excess power levels and can throw a relay to cut power to the transmitter.

IV. POWER DENSITY AT THE COMPACT RANGE FEED

Fig. 3 showed that the transmit beam from the AUT will impinge on the compact range reflector at full intensity with no space loss. At this point, the reflector will gather the received RF energy and focus that energy at the compact range feed aperture. The user must now determine the power density that will exist at the feed.

Hess [11] provides a derivation of the power transfer function of the compact range. Fig. 5 and Fig. 6 show the derivation of the power transfer function of the compact range as:

\[
\frac{p_{\text{REV}}}{p_0} = \left( \frac{\lambda}{4\pi R_0} \right)^2 G_{\text{AUT}} G_F
\]

This equation verifies the normal operational assumption that the Friis transmission formula applies to the compact range with the range length as the distance from the feed to the reflector. Note that \( R_0 \) is not the focal length of the reflector. The feed is usually pointed upward at approximately a 30 degree angle to balance the vertical taper of the quiet zone. For the 3.66 m focal length of the example, \( R_0 \) is 3.86 m.

Fig. 7 shows the derivation of the power density at the feed:

\[
S_{\text{FocalPlane}} = \frac{p_0 G_{\text{AUT}}}{4\pi R_0^2}
\]

Fig. 8 derives the power density ratio:

\[
\frac{S_{\text{FocalPlane}}}{S_{\text{AUT}}} = \frac{\lambda^2 G_{\text{AUT}}^2}{(4\pi R_0)^2}
\]

Note that if (7) is separated in logarithmic form, the two terms are the space loss for \( R_0 \) and twice the gain of the AUT. Fig. 9 shows an alternative representation in terms of the effective aperture of the AUT:

\[
\frac{S_{\text{FocalPlane}}}{S_{\text{AUT}}} = \left( \frac{\pi D_{\text{AUT}}^2}{4\lambda R_0} \right)^2
\]

A. Evaluating the Test Case

Applying these equations to the test case, the power density ratio is 12.2 dB or a linear factor of 16:6:1. For normal absorber with power handling of 775 W/m², the AUT power density can only be 46.7 W/m², well below the CW power density. Even using pulse techniques to reduce the duty cycle to 10% with 50 W/m², would present too much power at the feed. Further duty cycle reduction is an option.

Since this effect is localized when the main beam of the AUT is close to alignment with the compact range axis, application of high power absorber in the vicinity of feed aperture could be sufficient. A conservative recommendation would be to have all absorber within 8° of the feed be high power absorber. For high power absorber rated at 3500 W/m², an AUT power density of 211 W/m² at the AUT aperture could be supported.
V. CONCLUSIONS

As high power antennas are brought into the compact range, the user must determine the needs for high power handling. The process:

- Compute the power density of the AUT aperture via (1).
- Use one of the referenced calculations or approximations to determine the power density from 0.01 \( R/R_{ff} \) to 10 \( R/R_{ff} \).
- Note the distances to the absorber surfaces and whether or not high power absorber is needed or other mitigation must be applied.
- Note whether or not the FCC or ETIA human exposure criteria are exceeded and if usage guidelines or sensor alarm systems are needed.
- Determine the power transfer function from the AUT to the compact range feed via (7) or (8) and evaluate any further mitigation required.

These calculations can reduce the risk of hazards to the chamber and personnel in testing higher power levels in a compact range.

REFERENCES


Figure 1 Approximate Power Density vs. Range

Figure 2 Normalized Power Density for a Circular Aperture
Figure 3 Full Power Test Case Calculations

Figure 4 Test Case Pulse Modulated Adjustment

Figure 5 Model of the Compact Range

The criterion for the compact range to accept a plane wave is

$$R_0 \cdot \left(\frac{1}{2} \Delta \Theta\right) \leq \left(\frac{1}{2}\right)d$$

Therefore, the pass band of the compact range angular filter expressed in steradians is

$$\Delta \Omega = \pi \left(\frac{1}{2} \Delta \Theta\right)^2 = \pi \left(\frac{d}{R_0}\right)^2$$
**Figure 6 Compact Range Power Transfer Function**

- The Radiation Intensity of the Transmitting Test Antenna is
  \[ \Phi_{\text{AUT}} = \frac{dP_{\text{AUT}}}{d\Omega} = G_{\text{AUT}} \frac{P_0}{4\pi} \]
- The Power received by the Compact Range Angle Filter is
  \[ P_{\text{CR,Rev}} = \left( \frac{dP_{\text{AUT}}}{d\Omega} \right) \Delta\Omega = G_{\text{AUT}} \frac{P_0}{4\pi} \Delta\Omega \]
- Recall
  \[ G_F = \left( \frac{\pi d}{\lambda} \right)^2 \]
  \[ (\Delta\Omega) = \pi \left( \frac{1}{2} \frac{d}{R_0} \right)^2 \]
- Eliminating \( d \)
  \[ (\Delta\Omega) = \pi \left( \frac{1}{R_0} \right)^2 \left( \frac{\lambda}{\alpha} \right)^2 G_F = \left( \frac{1}{4\pi} \right) \left( \frac{\lambda}{R_0} \right)^2 G_F \]
- Combining gives the Coupling Equation
  \[ \frac{P_{\text{CR,Rev}}}{P_0} = \left( \frac{\lambda}{4\pi R_0} \right)^2 G_{\text{AUT}} G_F \]

**Figure 7 Power Density in the Focal Plane**

- The Power Density in the Focal Plane with the AUT Transmitting is
  \[ S_{\text{FocalPlane}} = \frac{P_{\text{CR,Rev}}}{A_{\text{Eff}}} = \frac{P_{\text{CR,Rev}}}{\frac{\lambda}{4\pi} G_F} \]
- Recall the Transmission Equation
  \[ \frac{P_{\text{CR,Rev}}}{P_0} = \left( \frac{\lambda}{4\pi R_0} \right)^2 G_{\text{AUT}} G_F \]
- Combining these gives
  \[ S_{\text{FocalPlane}} = \frac{P_0}{\lambda^2} G_{\text{AUT}} G_F \frac{\lambda}{4\pi R_0} \]
- of
  \[ S_{\text{FocalPlane}} = \frac{P_0 G_{\text{AUT}}}{4\pi R_0^2} \]
Figure 8 Power Density Ratio

From Earlier

\[ S_{\text{aper}} = \frac{P_0}{A_{\text{eff}}} = \frac{P_0}{\frac{\lambda^2}{4\pi} G_{\text{AUT}}} \]

\[ S_{\text{focal plane}} = \frac{P_0 G_{\text{AUT}}}{4\pi R_0^2} \]

Combining These Gives the Ratio

\[ \frac{S_{\text{focal plane}}}{S_{\text{aper}}} = \frac{P_0 G_{\text{AUT}}}{4\pi R_0^2} = \frac{\lambda^2 G_{\text{AUT}}}{(4\pi R_0)^2} \]

Figure 9 Alternative Power Density Ratio

From Previous Slide

\[ \frac{S_{\text{focal plane}}}{S_{\text{aper}}} = \frac{\lambda^2 G_{\text{AUT}}^2}{(4\pi R_0)^2} \]

But

\[ G_{\text{AUT}} = \left( \frac{\pi D_{\text{AUT}}}{\lambda} \right)^2 \]

Combining These Gives the Following Alternative Expression

\[ \frac{S_{\text{focal plane}}}{S_{\text{aper}}} = \frac{\lambda^2}{(4\pi R_0)^2} \left( \frac{\pi D_{\text{AUT}}}{\lambda} \right)^4 \]

\[ \frac{S_{\text{focal plane}}}{S_{\text{aper}}} = \left( \frac{\pi D_{\text{AUT}}}{4\lambda R_0} \right)^2 \]