Is there an angle to using Automated X-Ray Inspection?

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Introduction

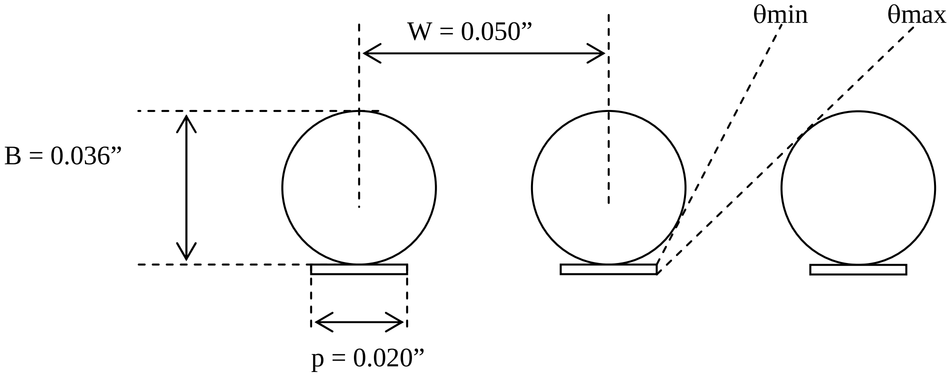
When reconstructing three dimensional slices to inspect double-sided PCBA's, there are many considerations to be made regarding the reconstruction technique used. Teradyne's ClearView technique uses our patented Off-Center Tomosynthesis reconstruction technique, this document discusses the various configurations of X-Ray absorbing parts on circuit boards, to determine the angles that are required to see around the obstructions. The following cases have been considered:

- Solder fillets under non-eutectic BGA (large ceramic BGAs use non-eutectic balls because they are taller, which reduces the thermal expansion stresses between the circuit board and the ceramic package).
- Stacked BGAs (identical BGAs on both sides of a board).
- Voids in solder fillets under non-eutectic BGAs.
- Column-grid array (CGA).
- Stacked CGAs.
- Ceramic capacitors.

Off-Axis Angle and BGA Ball Dimensions

In general, non-eutectic solder balls have a higher proportion of lead and so absorb more X-Rays than eutectic solder. This makes inspection of the solder fillet "through" a non-eutectic ball more difficult, and impossible at lower X-Ray energies. Therefore a more effective inspection technique is to see "around" the ball. The minimum angle required to see around the ball depends on the ball and pad dimensions.

Typically the pad is quite a bit smaller than the ball. For a 0.050" BGA[1], the balls are a nominal 0.030", and the pad may be either 0.020" or 0.024", depending on how many surface routing lanes are desired between pads. However the ball diameter tolerance is +/-0.006", so worst case we have a 0.036" diameter ball on a 0.020" diameter pad.



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[1] BGA ball and pad dimensions from Intel package database: http://developer.intel.com/design/packtech/packbook.htm (Intel's complete packaging guide) and http://developer.intel.com/design/packtech/ch_14.pdf (BGA section – note all Intel packages currently use eutectic solder balls)

If the pad diameter is p, the ball diameter is B, then the limiting angle at which the ball completely obscures the pad is given by:

$$\theta\text{min} = 90 - 2\tan^{-1}(p / B)$$

In the worst-case example above, θmin would be 32 degrees. For nominal-size balls, θmin would be 23 degrees.

The maximum angle, at which the next adjacent ball starts to obscure the view, is determined by W, the pitch between balls, and given by:

$$\theta\text{max} = 90 - 2\tan^{-1}(B / (2W - p))$$

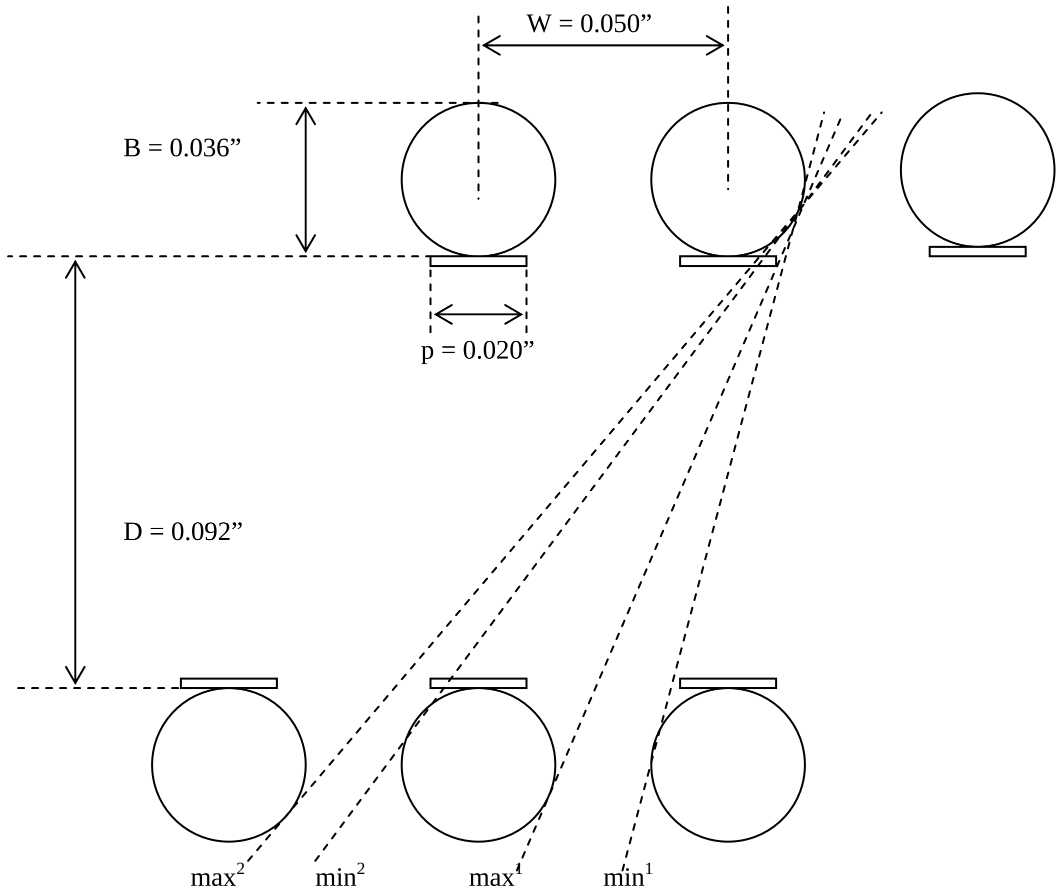
When W = 0.050”, B = 0.036”, and p = 0.024”, and θmax would need to be 39 degrees.

Texas Instruments package guide for 0.8mm pitch BGA indicates a 0.5mm ball and a 0.35mm pad. Again, these are eutectic balls. In this example θmin would be 20 degrees, and θmax would be 46 degrees, for nominal-size balls.

The balls in the example are not completely opaque, and penetrating the edge of the ball is in most cases OK. The requirement is to see the solder fillet in order to detect it.

Stacked BGAs

For dense, double-sided, high-performance boards, it is not unusual to stack 2 BGAs directly opposite each other. So the angle required to see around the BGA balls depends not only on the ball/pad dimensions of one BGA but also on the dimensions of the other BGA (which we will assume are the same as the first) and the circuit board thickness, D.



We need to be able to look around the balls of the top-side BGA while looking through the spaces between the balls of the bottom-side BGA. There are N possible spaces that we can look through, but the first two are the most useful, defining the ranges min^1 to max^1, and min^2 to max^2, defined as follows:

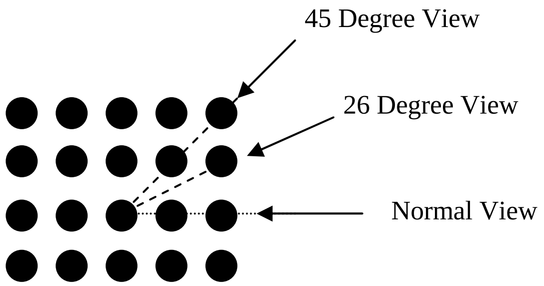
$$min^1 = \sin^{-1}(B / (B + D))$$
$$max^1 = \tan^{-1}(W / (B + D))$$

$$min^2 = max1 + \sin^{-1}(B\sin(max^1) / W)$$
$$max^2 = \tan^{-1}(2W / (B + D))$$

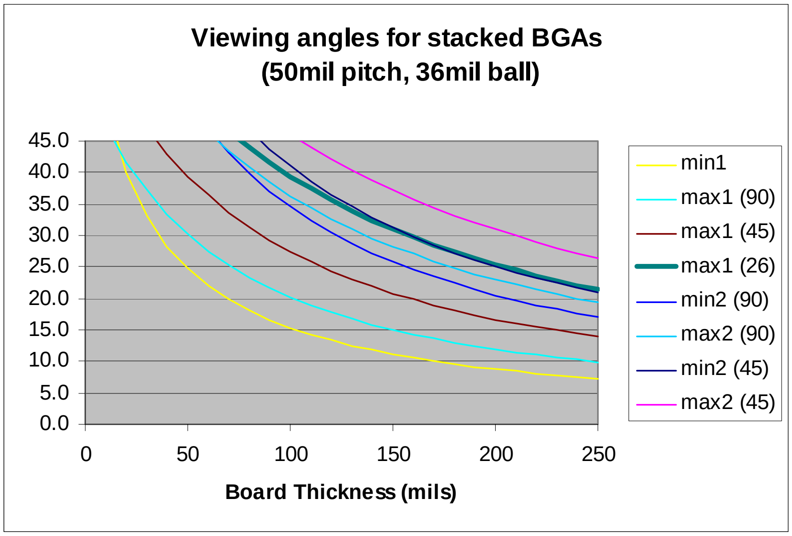
For the worst-case situation of 36mil balls on 50mil pitch, and a typical 93mil board thickness, the spaces are 16 to 21 degrees, and 36 to 38 degrees.

If we view diagonally at 45 degrees to the X axis, which has the effect of increasing W by a factor of $\sqrt{2} = 1.414$, we can extend the first space out to 29 degrees and still see the solder fillet.

There is also another view between adjacent balls, at a diagonal angle of about 26 degrees. This has the effect of increasing W by a factor of $\sqrt{5} = 2.236$. This gives a clear shot of the middle of the solder fillet. However, since we're looking between the adjacent balls that could be up to 36mils in diameter, only the central 14mils of the pad region is guaranteed to be unobstructed. But by combining multiple views, the entire solder fillet can be imaged.



The following chart shows how the viewing spaces vary with board thickness for a worst-case 36mil ball.

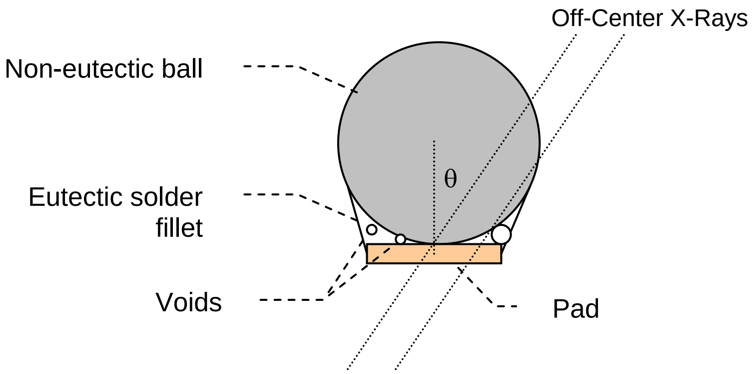


Using the view at 26 degrees (shown as a thick line), there are no obscurations for any angle up to 30 degrees, for board thickness up to 3 times the BGA pitch. Switching to a 45 degree view for thicker boards enables fault detection on board thickness equal to 4 times the BGA pitch.

Voids in solder fillets under non-eutectic BGAs

With non-eutectic BGAs, the volume of eutectic solder is generally quite small. Voids in the eutectic solder fillet can cause the fillet to crack. Multiple small voids are just as much a problem as a single large void. Inspection for voids in the fillet requires the X-Ray system to look at least partially through the non-eutectic solder ball.

If the void is in the solder fillet under the ball, the size of a spherical void is limited by the thickness of the eutectic solder fillet at that point. In order to minimize surface energy, voids will tend to assume a spherical shape. If a small void is caught under the ball and gets squashed, it will tend to drift outwards until there is enough room for it to be a sphere. Thus, a void will typically not be found near the center of the pad. Consider the largest possible spherical void that could fit in the solder fillet between the ball and the pad, assuming the solder ball is pulled down onto the pad during soldering:



For a void at a radius r from the center of the pad, and a ball diameter B, the maximum diameter of a spherical void is given by:

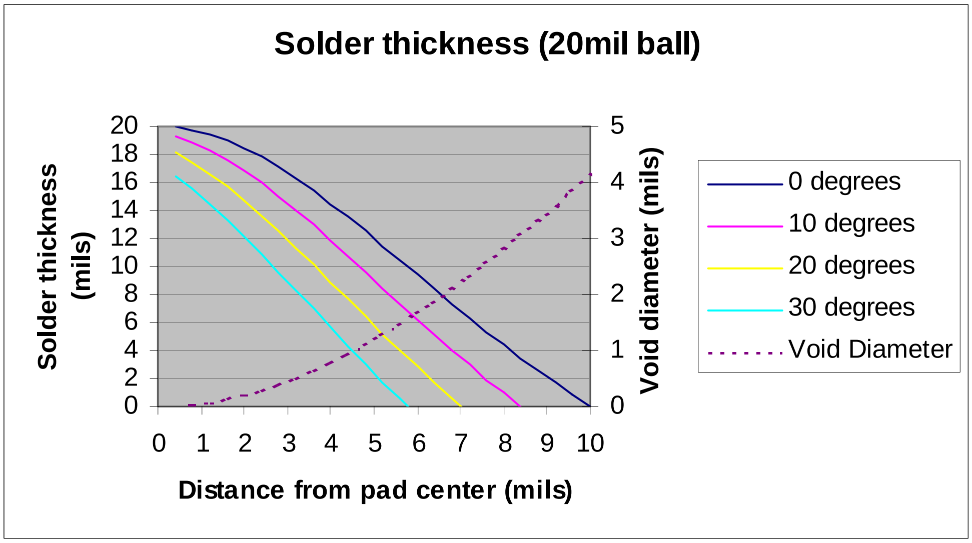
$$\frac{1}{2}\left(\sqrt{B^2 + 4r^2} - B\right)$$

In a typical case where B = 20mils, r = 7.5mils (15mil pad diameter), the void diameter is about 2.5mils.

For voids at a radius r from the center of the pad, X-rays must pass through the solder ball and the eutectic solder fillet. Assume the void is large enough to displace most of the eutectic solder, and so we just consider the thickness of non-eutectic solder in the ball. For off-axis X-Rays at an angle θ to the vertical, this thickness is given by:

$$B\cos(\theta + 2\tan^{-1}(2r/B))$$

Curves for various values of r and θ are plotted in the next chart, along with void diameter. Note the near-linear relationship for values of θ in the 20° to 30° range.



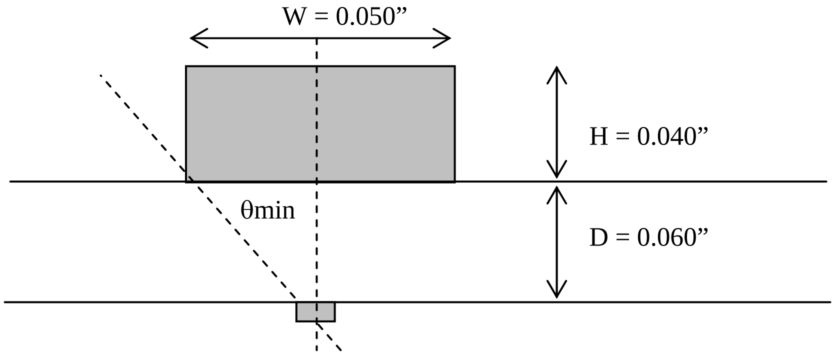
A high speed transmission X-Ray system such as Teradyne's XStation can detect voids about 20% of the ball diameter, limited by signal-to-noise. Thus it can see a void when the thickness of solder is 4 times the void diameter, or less. On the above chart this occurs around 6.6mils out from the pad center, when the void size is 2mils and the solder thickness is 8 mils. This point is conveniently found where the dotted line crosses the 0-degree line.

Using Tomosynthesis imaging, the system is capable of detecting smaller voids, as small as 1mil for a 30-degree angle.

Ceramic Capacitors

The other consideration for off-axis angle viewing is ceramic capacitors. These are large, dense objects containing materials of high atomic number. They are not completely opaque to high-energy X-Rays, but they are very dark.

Attempting to inspect "through" the capacitors may work with high energies and small capacitors (0201 and 0402, maybe 0603) but may be troublesome for larger, thicker parts (0805 and 1206).



For example to be able to inspect around a 0805 capacitor (of width W = 0.050") on circuit board (of thickness D = 0.060"), a minimum angle θmin is required, given by:

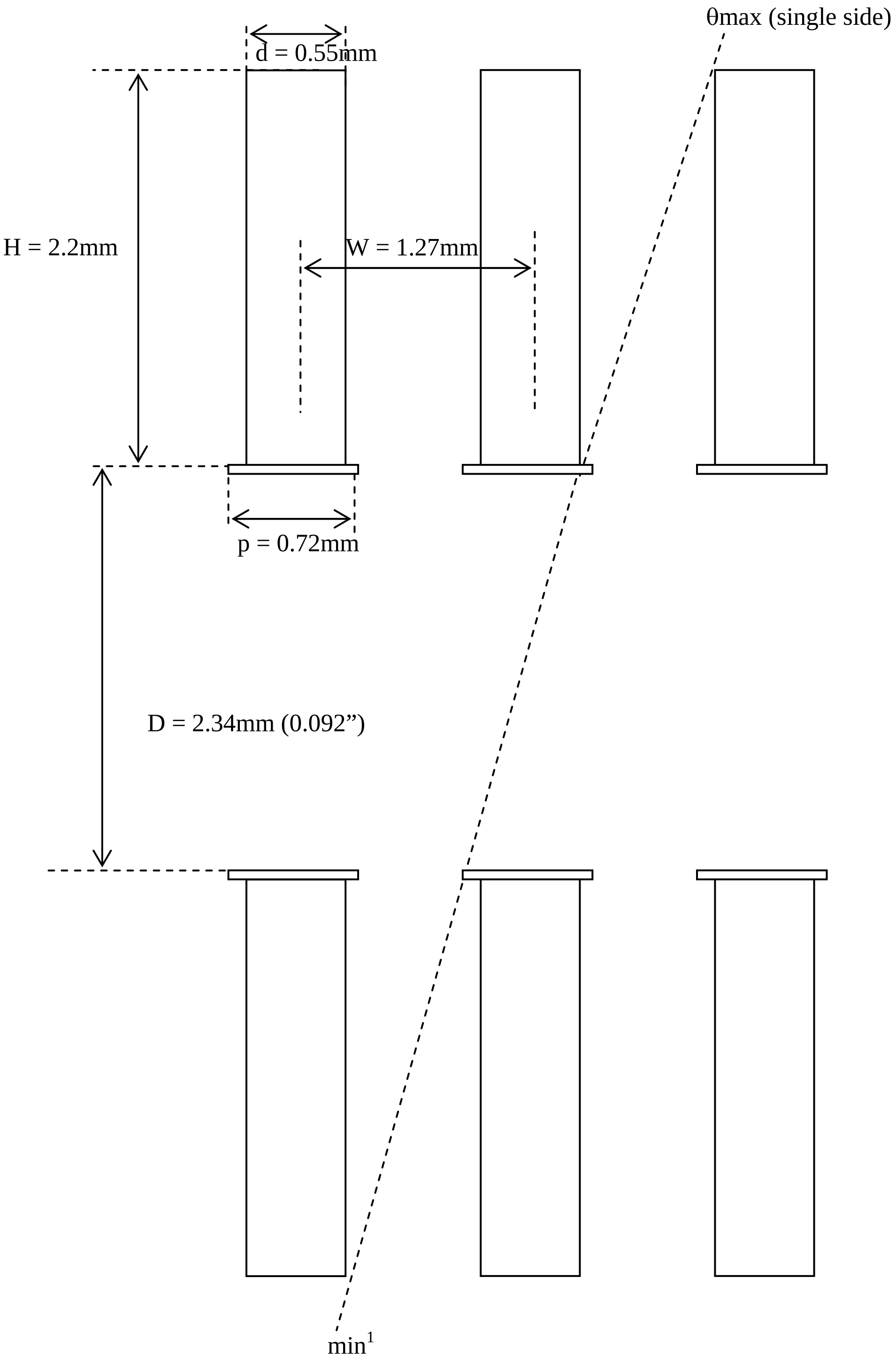
$$\theta\text{min} = \tan^{-1}(W / 2D)$$

In this example θmin would be 23 degrees.

CCGAs (Ceramic Column Grid Arrays)

For ceramic column-grid arrays, there are two pitches commonly in use. The following data is referenced from IBM:

Pitch (W)	**1.27mm**	**1.00mm**
Column Height (H)	2.01mm – 2.41mm	1.27mm nominal
Column Diameter (d)	0.45mm – 0.65mm	0.50mm nominal
Pad Diameter (p)	0.72mm	0.67mm



For a single-sided application, the solder fillet can be observed using transmission X-Ray. However, for all except the steepest of angles, the fillet will be partly obscured by the solder column. Thus an angled view is preferred. The maximum viewing angle to see the solder fillet at the base of the column is:

$\theta\text{max} = \tan^{-1}((W-d) / H)$
$\theta\text{max (1.27mm pitch)} = 18^\circ$
$\theta\text{max (1.00mm pitch)} = 21^\circ$

Using a diagonal 45° view, W is increased by a factor of $\sqrt{2}$ and the angles increase to 30° and 36° for 1.27mm and 1.00mm pitch respectively.

For a stacked configuration, the minimum and maximum viewing angles to see the solder fillet at the base of the column are:

$\text{min}^1 = \tan^{-1}((p + d) / 2D)$
$\text{max}^1 = \tan^{-1}(W / (H + D))$

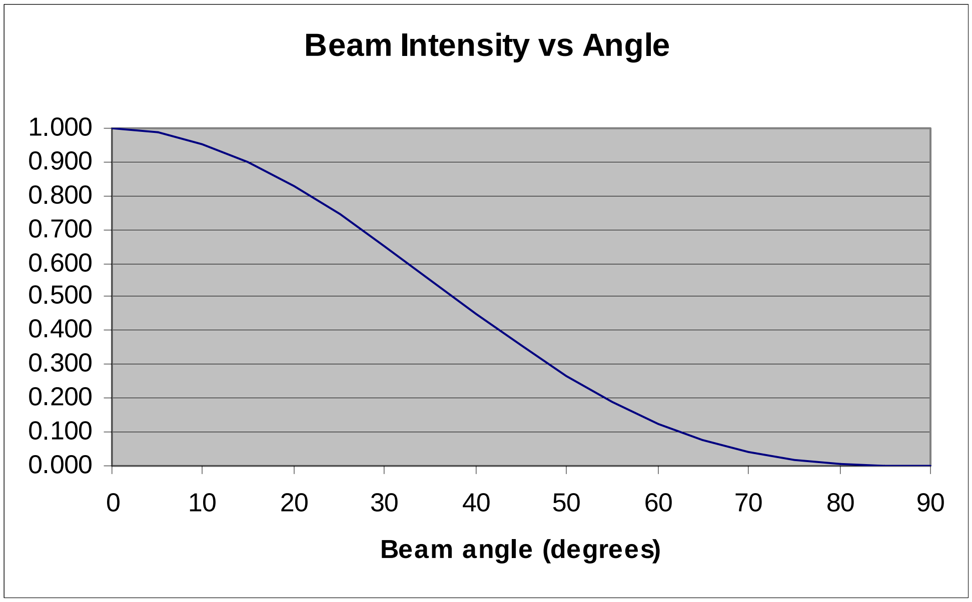
For a 0.092” (2.34mm) thick PCB, $\text{min}^1 = 15^\circ$ and $\text{max}^1 = 16^\circ$. For PCBs thinner than the column height the normal view of the stacked configuration is completely obscured. Using a diagonal 45° view, $\text{max}^1 = 21^\circ$, which offers a small range of viewing angles, though not the same angles as would typically used during Tomosynthesis. Using a 26° diagonal view gives $\text{max}^1 = 32^\circ$. However, just as with BGAs, although only the central part of the solder fillet can be seen in this view.

Intensity Variation Across the Field-of-View

The X-ray beam energy varies from the center to the edge.

Using simple $1/r^2$ calculations, for a field-of-view subtending angle 2θ of the X-ray source, the intensity at the edge of a flat detector is $I_1 = I_0\cos^3\theta$, where I_0 is the intensity at the center. So for oblique-angle imaging at 30 degrees, the intensity is about 65% of the central intensity.

The chart below shows how beam intensity ($\cos^3\theta$) varies with θ



Clearly, the large angles (anything over 45 degrees) have severe intensity reduction.

This chart described the X-Ray attenuation in air. When viewed at an angle, all the PCB objects also appear thicker by a factor of 1/cosθ, thereby increasing the absorption as well. The exceptions, of course, are solder balls, which are round.

Summary:

The results show that angles greater than 23 degrees are required for inspection of non-eutectic BGAs, and angles around 30 degrees are preferred. Angles greater than 39 degrees are of limited usefulness for BGA inspection due to obscuration by adjacent balls.

A solution that uses Multiple angled X-ray for reconstruction has the best inspection capabilities. Teradyne’s Off-Center Tomosynthesis techniques use a range of angles between 23 and 39 degrees across the Field Of View (FOV) to provide the maximum coverage.