ACADEMIC STUDY
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Shot Peening Coverage Requirements

INTRODUCTION

Users require that their components should be peened to specified levels of coverage. They also require that the shot stream used has specified characteristics – such as intensity, shot size and type. The term "coverage" is well-understood as being the percentage of the peened surface that has been indented at least once. Testing for coverage is quite independent of testing for intensity and should be determined using specified procedures – such as those described in SAE J2277 "Shot Peening Coverage Determination."

Every experienced shot peener is familiar with the effect of shot peening time on coverage evolution. Fig.1 is very similar to the coverage/amount-of-peening curve published as fig.3 of SAE J443, 1952. The shape of the curve shown is called "exponential" because the coverage value can only approach 100% but never quite reaches it. Coverage is the sum of the contributions made by numerous individual indents. These indents are being created at what is called the "indent rate."

The greater the coverage the greater is the chance that a new indent will overlap a previous indent – or even hit a cluster of previous indents and make no contribution to coverage at all. This is illustrated by fig.2.

In specifying their coverage requirements many customers consider that "more peening is better". Hence we encounter requests such as 200% and 300%. It should be kept in mind, however, that it is not the dents themselves that improve the service performance of peened components. Improvement comes primarily from surface residual compressive stress and also, but to a lesser extent, surface work-hardening. There is a growing realization that maximum compressive residual stress levels and optimum work-hardening generally occur with significantly less than 100% coverage. Hence, in general, "more peening is not better." Carburized components provide an interesting parallel. Optimum fatigue performance generally coincides with the presence of a small percentage of retained austenite in the final, tempered, structure. Myriads of tiny austenite particles act as 'escape routes' for dislocations being piled up that would otherwise initiate fatigue cracks.

One formal definition of coverage is that contained in SAE J2277, 2009:

> *"Coverage is defined as the percentage of a surface that has been indented at least once by the peening media. It is, however, very difficult to obtain accurate measurements of coverage above 98%. "Full coverage" is therefore defined as being at least 98% denting of the surface to be peened. Coverage above "full coverage," when required, is obtained by peening for multiples of the time required for "full coverage."*

This J2277, 2009 definition of "full coverage" is flawed by the inclusion of the words "at least". This, unintentionally, allows any amount of peening above 98% coverage to satisfy the "full coverage" requirement. The flaw is currently being corrected by substituting the word "approximately" for the words "at least."

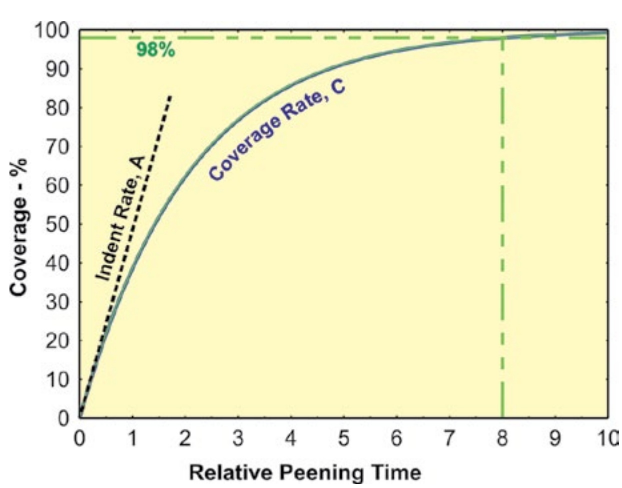


Fig.1. Relationship of Coverage to Peening Time and Indent Rate.

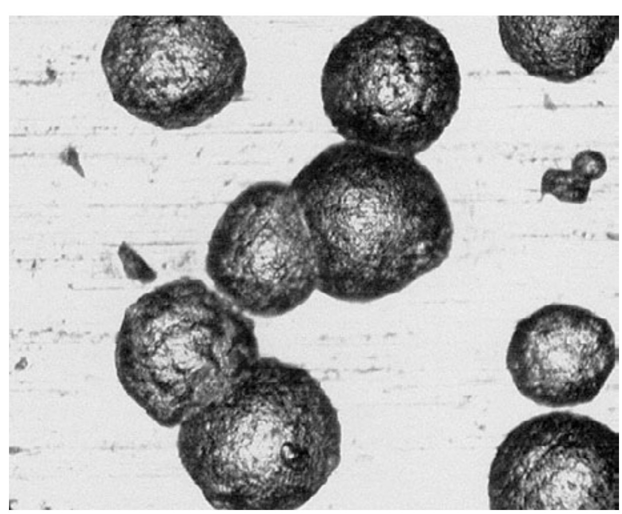


Fig.2 Micrograph of shot peened steel showing overlapping indents.

Shot peening coverage requirements are probably best specified with reference to "full coverage" – where that corresponds to "approximately 98%". Anything greater than 98% coverage should only be required if there is proof that it does not detract from optimum component performance.

Shot peeners have to adjust the amount of peening applied to components in order to satisfy whatever coverage level has been specified by the customer. A quantitative relationship between coverage and amount of peening has been available for sixty years – described in SAE J443 1952. This relationship together with other useful relationships is presented in this article. No mathematical ability is needed to use these relationships. All that is necessary is the ability make a single coverage measurement and to insert the result into an appropriate computer program.

FULL COVERAGE

A pictorial approach aiming at 98% coverage is illustrated by fig.3. This approach starts with the assumption that coverage is measured after one pass (or equivalent time unit). If this is found to reach 98% then the objective has been reached. If, however, it is less than 98% then further passes (or extra time) would be needed. Fig.3 shows how many passes in total would be needed to achieve 98%. This includes any first-pass coverage of over 32% (less than 32% would correspond to an uneconomical situation).

Passes to reach 'Full Coverage'	Measured 1 Pass Coverage
1 PASS	98%+
2 PASSES	<98% >86%
3 PASSES	<86% >73%
4 PASSES	<73% >62%
5 PASSES	<62% >54%
6 PASSES	<54% >48%
7 PASSES	<48% >43%
8 PASSES	<43% >39%
9 PASSES	<39% >35%
10 PASSES	<35% >32%

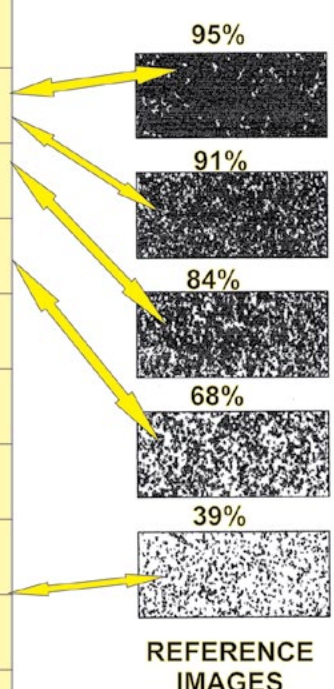


Fig.3. Predicting passes needed for 98% coverage using Reference Images.

If, for example, a coverage of 58% was measured after one pass then a total of five passes would be needed. The 'green-to-red' shading of the passes to reach 'full coverage' is indicative. Hence, if the one pass coverage was, say, 54.5% then it would be in a red shaded area. That indicates that caution must be taken in assuming that a total of only five passes is needed - because complete reliance is being placed on the accuracy of one measurement. Conversely if the one pass coverage had been, say, 61% then there would be a 'green' indication that a total of only five passes could be relied on.

The arrows from the reference images in fig.3 show the corresponding points on the table of pass requirements.

COVERAGE/AMOUNT OF PEENING RELATIONSHIPS

A quantitative relationship between coverage and amount of peening is essential for the proper control of coverage. Such a relationship has to solve the problem of the diminishing contributions of impacts to coverage as peening progresses. This problem was solved as early as 1939 by M. Avrami.

1) Avrami Equation

Avrami's simplest equation (one of several that he produced) is commonly employed to relate coverage to the amount of peening. This fundamental relationship can be expressed as:

$$C_t\,\% = 100[1 - \exp(-A{*}t)] \qquad (1)$$

where C_t % is the coverage after a time **t** and **A** is the indent rate.

A is the ratio of **total area of indents to targeted area produced in 1 unit of peening time. t** is the number of peening time units used. Imagine, for example, that 500mm^2 of indents are applied in one pass (t=1) to each 1000mm^2 of component surface. The indent rate, **A**, is then 0.5 per pass. With two passes the time, **t**, becomes equal to 2.

If **= 100*(1 – EXP(-0.5))** is typed into the formula bar of an Excel spreadsheet for a pre-selected cell, then it would give the value of 39.3. That is Avrami's equation at work, allowing for the overlapping that must have occurred. Substituting 1.0 for the 0.5 in the formula bar would give the answer 63.2. This example shows that a coverage of 39.3% would have resulted from applying an indent rate of 0.5 for 1 pass and 63.2% would have resulted from applying 2 passes.

2) Coverage based on one measured value of coverage

Equation (1) is mainly of academic interest - since the indent rate, **A**, is rarely measured during practical shot peening. What is commonly measured is the coverage that was actually achieved in 1 unit of 'time' e.g. 1 pass. Equation (1) can be written as:

$$A = -\ln[(100 - C_1)/100] \qquad (2)$$

where **ln** stands for 'natural logarithm' and C_1 is the coverage % measured after 1 pass.

Using the previous example, typing = **-LN((100 – 39.2)/100)** into the formula bar of an Excel spreadsheet would yield **0.50** as the value for **A**. Substituting 63.2 for the 39.3 would yield **1.0** for the value of **A**. This simply shows that the same values arise when working backwards.

The great value of equation (2) is that it can be used to determine the indent rate, **A**, that has been applied when a coverage of $\mathbf{C_1}$ has been measured. This value of **A** can then be substituted into equation (1) – thus enabling prediction of the coverage that would arise for any given number of passes (or time units). This two-stage mathematical operation is built into the author's Excel-based "Coverage Predictor Program."

When SAE J443 was published in 1952, universal access to computers was not available. A modified form of equation (1) was included so that only a single-stage mathematical operation was needed to predict multi-pass coverage based on a single measurement – $\mathbf{C_1}$. Even that operation could be avoided by using the included "nomograph." This was a straight-line relationship achieved by using "log-log" paper. The modified form of equation (1) used was that:

$$\mathbf{C_2 = 1 - (1 - C_1)^n} \qquad (3)$$

where $\mathbf{C_1}$ = % coverage (decimal) after 1 pass and $\mathbf{C_2}$ = % coverage (decimal) after **n** passes.

Equation (4) is simply equation (3) written in non-decimal format and with n replacing the **2**.

$$\mathbf{C_n = 100(1 - ((100 - C_1)/100)^n} \qquad (4)$$

where $\mathbf{C_1}$ = % coverage after 1 pass and $\mathbf{C_n}$ = % coverage after **n** passes.

Substituting the value of 39.3% for $\mathbf{C_1}$ (obtained earlier) and **n = 2** into equation (4) gives a predicted coverage (for 2 passes) of 63.2%. That is precisely the same value as was predicted using the original Avrami equation. This is not unexpected because **equations (1) and (4) are the same** – they are just presented differently. They will always give the same predicted answers. The proof of this equivalence of the 1939 Avrami and 1952 J443 equations is only of academic interest. A mathematical proof of the equivalence follows because the statement must withstand academic scrutiny.

Proof of Equivalence of Avrami and J443 equations

This proof traces the conversion of the Avrami equation into the J443 equation.

Avrami $\qquad C_n = 100(1 - exp(-A*n)) \qquad (a)$

But $exp(-A*n) = (exp(-A))^n$ *so that (a) can be written as:*

$$C_n = 100(1 - (exp(-A)^n) \qquad (b)$$

When n = 1 equation (b) becomes:

$$C_1 = 100(1 - exp(-A)) \text{ so that}$$

$$exp(-A) = (100 - C_1)/100 \text{ so that}$$

$$exp(-A)^n = ((100 - C_1)/100)^n = exp(-A*n)$$

Substituting $((100 - C_1)/100)^n$ *for* $exp(-A*n)$ *in equation (a) gives:*

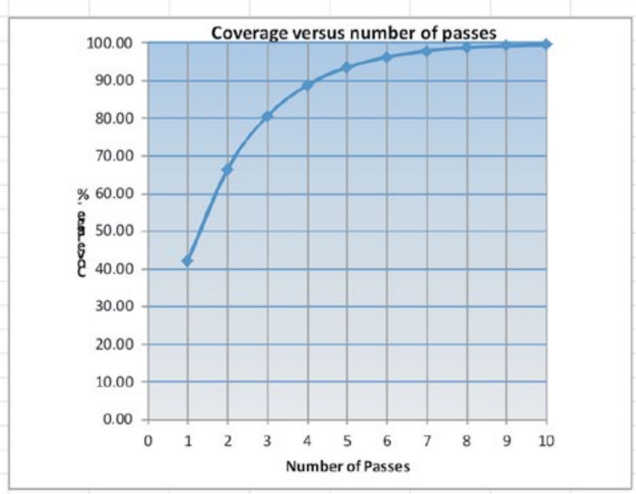
J443 $\qquad C_n = 100(1 - ((100 - C_1)/100)^n) \qquad (c)$

Equation (c) is exactly the same as the non-decimal form of the J443 equation given as equation (4). ***Q.E.D.***

COVERAGE PREDICTION PROGRAM AND ITS APPLICATION

A simple Coverage Prediction program has been produced and is available free from www.shotpeener.com. Fig.4 shows a program example with the first data point inserted, as instructed. Numerical predicted coverage values are given – which saves having to read them from the graph. The program calculates the A-value by using equation (2) and then predicts coverages using equation (1).

No. of Passes	Coverage - %
1	42.00
2	66.36
3	80.49
4	88.68
5	93.44
6	96.19
7	97.79
8	98.72
9	99.26
10	99.57
A - value	
0.545	



INSTRUCTIONS: Enter measured value of coverage into Cell B2

Fig.4. Example showing application of Coverage Prediction program.

As an example of coverage prediction accuracy, consider the following real situation. A set of measured coverages (not made by the author) are given in Table 1.

Table 1. Measured Coverages using S230 shot.

No. of Passes	Measured Coverage - %
1	42
2	68
4	84
6	95
8	98.5

Fig.5 shows the data points of Table 1 plotted together with (a) a coverage prediction curve using the first data point as C_1 in equation (2) and (b) an Avrami curve best-fitting to the set of data points. It can be seen from fig.5 that the predicted and actual curves are very close to one another. The actual data points do not lie exactly on the best-fitting curve – as would be expected.

It is important to note that the equations described previously rely on the value of coverage actually measured after a known 'time'.

PRE-PLANNING VERSUS POST-MORTEM

Pre-Planning

The previous section showed how coverage can be predicted by using pre-planning. With pre-planning, coverage is measured for one unit of applied peening time (such as that for a single pass) This can then be used to calculate the coverage that will be achieved after multiples of that time unit.

Post-Mortem

An alternative to pre-planning is to use a post-mortem approach (for want of a better phrase). With this approach the shot peener assumes beforehand that the required coverage will be achieved in a known number of time units. For example: it was assumed that 98% coverage would be achieved with 6 passes. On examination it was found that the coverage was only 96%. The obvious question then is "How many extra passes would be needed to achieve 98% coverage?"

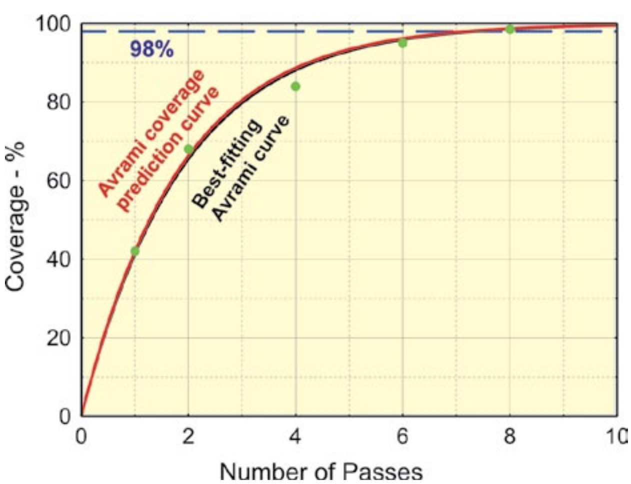


Fig.5. Avrami coverage prediction and 'best-fitting' curves for data given in Table 1.

The following is a description of how 'post-mortem' calculations can be made. These calculations can be carried out using a modified version of the Coverage Predictor program – without needing to understand the procedure that follows.

Equation (2) can be modified to allow for the measured coverage being $\mathbf{C_n}$ occurring after **n** passes:

$$\mathbf{A = -ln[(100 - C_n)/100]/n} \qquad (5)$$

The value derived using equation (5) is then substituted into equation (1) using t = 1 to derive $\mathbf{C_1}$. This derived value of $\mathbf{C_1}$ for the 'required value' is then used in the Coverage Predictor program. As an example: if coverage after 6 passes was measured to be 96% then substitution in (5) would give that **A = 0.536**. Substituting that value into equation (1) with **t = 1** would give that $\mathbf{C_1}$ **= 42%**. Substituting $\mathbf{C_1}$ **= 42%** into the Coverage Predictor program would produce the results shown as fig.6 on page 32. From that it is predicted that **8 passes** would give 98% coverage – rather than the 6 passes which gave 96%. Fig.6 shows Sheet 2 of the modified Coverage Predictor program that has carried out the calculations automatically.

EFFECT OF INDENT RATE ON COVERAGE

Customers generally specify the shot type and peening intensity that has to be applied to their components. Shot flow rate and applied peening time are then the only coverage control factors available to the shot peener. Doubling the shot flow rate would double the indent rate - <u>but only if the peening intensity was also maintained</u>. Fig.7 (page 32) illustrates the effect of different indent rates on coverage evolution. The range of indent rates shown is not enormous – simply ten to one.

It follows from fig.7 that an indent rate of less than 0.4 is going to be impractical for most purposes - more than ten passes being needed to achieve 98% coverage. An enlightened customer requiring a minimum of 85% coverage could be accommodated with an indent rate of only 0.2 - provided that at least 10 passes were applied. A second important conclusion from fig.7 is that shot flow control is very important when it comes to controlling coverages. For example, if an indent rate achieved 98% coverage in 4 passes then a 10% drop in flow rate would mean that an extra pass would be required.

ASSESSMENT OF COVERAGE

Assessment of the coverage after 1 pass is critical for pre-planned coverage control. Assessment of the fully-peened

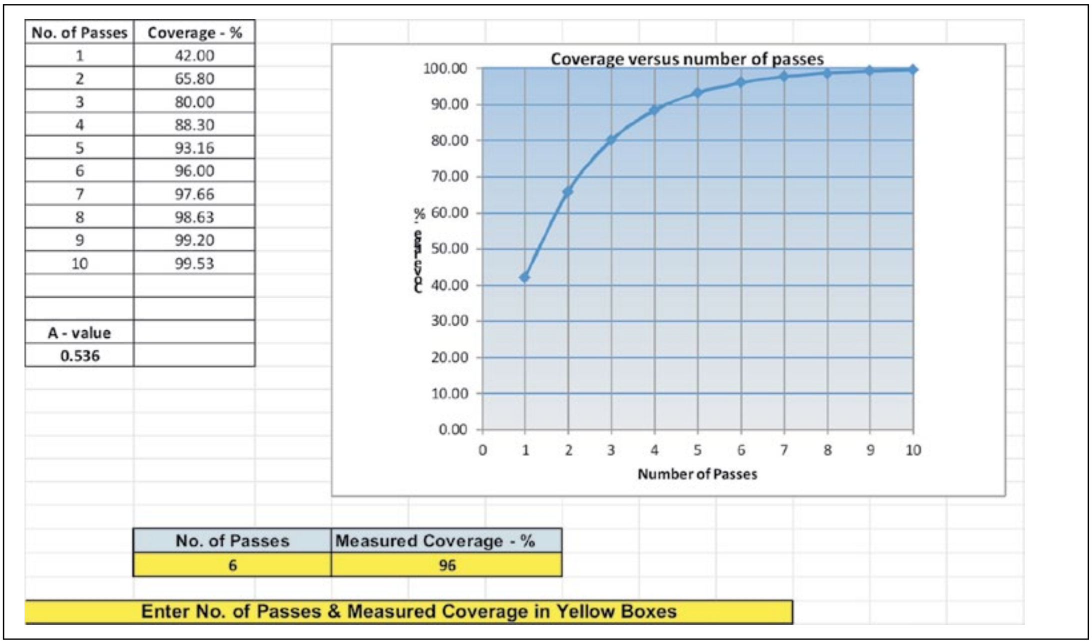


Fig.6. Coverage Prediction after one coverage measurement at six passes.

component is also critical if the customer's requirements are to be satisfied. The more accurate the coverage assessment the easier it will be to achieve both objectives. A basic premise is that coverage assessment is most accurate when the coverage is 50% - when there are equal amounts of peened and unpeened areas.

There are a number of practical methods of coverage assessment. The simplest combination is probably that of an operator using a 10x magnifying glass and mentally comparing the images with those stored in a human memory. This should not be under-rated as a method. Experienced operators can accurately assess coverage – certainly to better than 5% at low coverages and to better than 2% at high coverages.

Image capture is vital if a record of the coverage is to be retained. There are many applicable devices, most of which

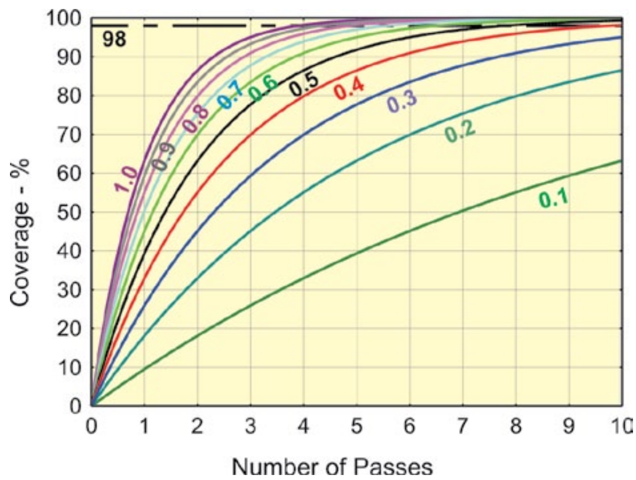


Fig.7. Effect of Indent Rate on Coverage evolution.

now involve recording a digital image of the peened surface. The surface may be directly photographed using the zoom facility of a digital camera or may involve a digital camera/ microscope combination. It follows that the better the optics the better will be the quality of the recorded image.

All coverage assessment methods require some form of image reference. Reference images are included in fig.3 but a set of digitized images is of much better practicality. Digitized reference images can be computer-manipulated to match the lighting conditions and surface reflection behavior of shot peened components.

A useful reference set is that shown as fig.8 (page 34). This set of computer-generated images was kindly supplied by Dale Lombardo of GE Energy. The supplied images are shown (in grayscale) as the left column and after computerized color-inversion (white to black) on the right.

DISCUSSION

Satisfying customers' coverage and peening intensity requirements are the two prime objectives for shot peeners. The procedures described in this article allow optimization of coverage satisfaction. The equations presented are robust, well-tried, and agree closely with measured coverage evolution.

The controlling factors for coverage attainment are indent rate and peening time. Indent rates are easily deduced and employed in coverage prediction. Deduced indent rates are surprisingly constant - provided that the shot stream itself remains constant. Changing the flow rate in order to change the indent rate has attendant problems: (1) media flow rate can affect air blast media velocity and (2) excessively high flow rates might result in congestion at the surface - rebounding media interfering with incoming media. It follows that if the flow rate is changed then a new coverage measurement has to be made.

Predicted coverages using time multiples are accurate if one coverage measurement is made when approximately 40-60% coverage has been applied. Confirmation of achieving a high level of coverage is, however, difficult. Reference images are very useful, particularly when attempting to assess high coverage levels.

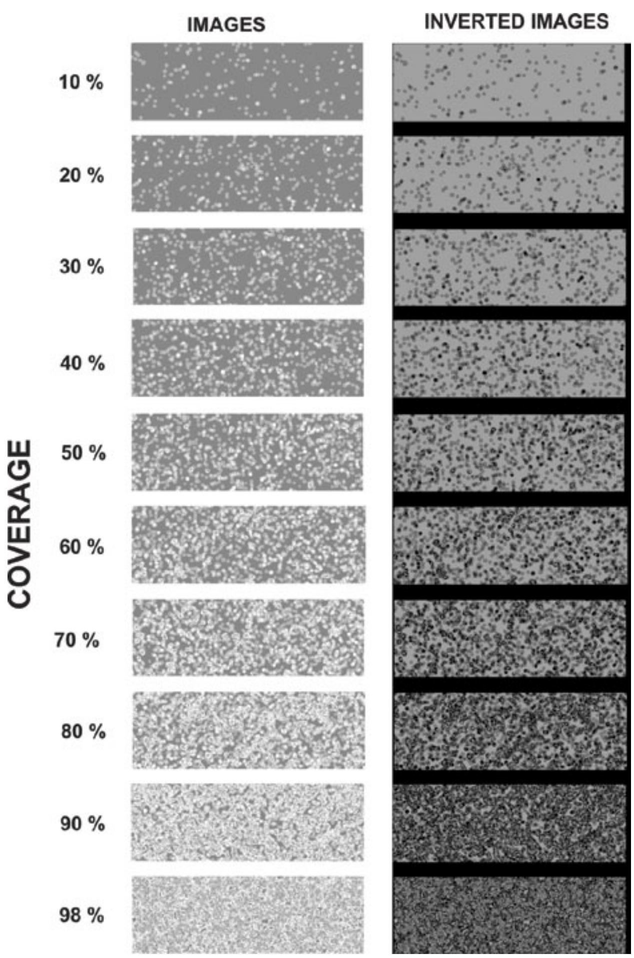


Fig.8. Computer-generated reference images. Courtesy of Dale Lombardo, GE Energy.