Meaning, Measurement Philosophy and Verification of "Peening Intensity"

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INTRODUCTION

"Peening intensity" is the depth-inducing capability of a shot stream. Shot peening causes plastic deformation of component surfaces - inducing compressive residual stress in the deformed surface layer. The depth of the plastically-deformed layer needs to be controlled. Shot streams have several properties that allow us to control the depth. Consider, by way of analogy, a stream of bullets fired by a machine gun. That stream has the ability to surface damage a target. This ability depends on the size, velocity and hardness of the bullets. Large, hard-nosed, bullets fired at high velocity will generate much deeper surface damage than will small, soft-nosed bullets fired at low velocity. A clear parallel can be drawn with the depth-inducing capability (peening intensity) of a shot stream.

"Peening intensity" is the parameter used to define and regulate the depth-inducing capability of a shot stream. When shot peening was in its infancy, J. O. Almen recognized the need for quantification of this capability. He conceived the brilliant idea of measuring the depth-inducing capability indirectly - by measuring the deflection induced in a set of steel strips peened for increasing periods. The term "Saturation Curve" was coined to describe the increase in peened strip deflection that occurs with increased peening time. A particular point on that curve, "Peening Intensity," is used to quantify a shot stream's depth-inducing capability. The greater the strip deflection at that point the greater is the shot stream's capability. The equipment and procedures needed to estimate peening intensity are detailed in standard specifications J442 and J443.

This article addresses three major problems associated with "peening intensity" – attempting to provide at least partial solutions. These problems concern the actual meaning, measurement philosophy and verification of peening intensity.

MEANING OF PEENING INTENSITY

"Peening intensity," part of the specialized vocabulary that is employed by the shot peening industry, is used to regulate the depth of the compressively-stressed layer that is induced when a shot stream bombards a component. As peening intensity is increased so does the depth of the compressively-stressed layer – other things being equal. This is illustrated schematically by fig.1. We know then that the depth of the compressed layer is directly related to the peening intensity of the shot stream. The units of peening intensity are the same as those for depth of induced compressed layer – micrometers (or thousandths of an inch).

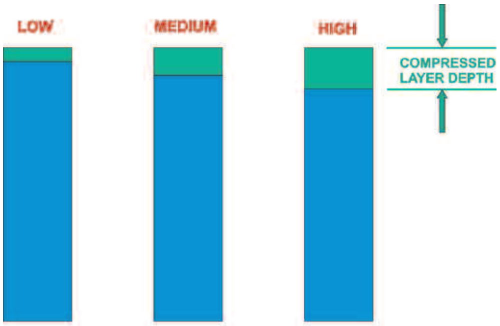

Fig.1 Influence of Peening Intensity on depth of compressed surface layer – as induced at "full coverage."

Of itself, a shot stream has only a potential peening intensity (depth inducing capability). This potential is realized, to a greater or lesser extent, when the shot stream impacts a targeted component. Consider again, by way of analogy, the stream of bullets fired by a machine gun. That stream has the potential to surface damage a target. A parallel can again be drawn with the potential depth-inducing capability (peening intensity) of a shot stream.

It is very important to appreciate that:

peening intensity varies with distance

This variation is illustrated schematically, for an air-blast stream, by fig.2. In essence, shot continues to be accelerated by the faster-moving air stream as it exits from the nozzle. Deceleration is, however, provided by the surrounding static air. The combined acceleration/deceleration produces a maximum shot velocity at some distance, **M**, (usually some 200-300mm for commercial peening equipment). With wheel-blast machines deceleration starts as soon as the shot leaves a blade.

If we compare peening at a distance **M** with that at some greater distance from the nozzle, **x**, two features of practical importance are apparent. The first is the obvious difference in peening intensity at the two positions. The second is that there is almost no variation of intensity with distance fairly close to **M** whereas there is an obvious range of intensity fairly close to **x**.

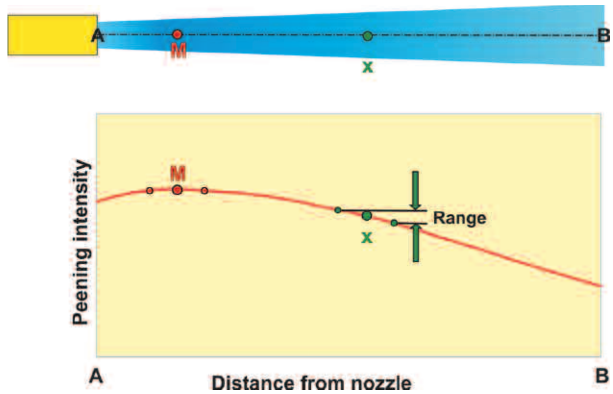

Fig.2 Variation of potential peening intensity with distance from nozzle.

There is a small variation in potential peening intensity across the section of a shot stream. This variation is, fortunately, not important - because the shot stream is moved tangential to the targeted component.

The impact effect of either bullets or a shot stream will depend on the target's properties – thickness, hardness, inclination to the stream, etc. We can extend the machine gun analogy to include measurement of impact effect. Sheets of body armor placed in the "line of fire" will be indented to an extent that depends on the surface damage potential of the bullet stream. In order to quantify this potential we would need a test with standardized sheets (in terms of material, hardness and thickness) placed at 90˚ to the stream and at a known distance from the gun's nozzle.

MEASUREMENT OF PEENING INTENSITY

There is currently no method available that can directly measure the potential peening intensity of a shot stream. We have to rely on measuring the impact effect of the shot stream on Almen strips placed at 90˚ to the shot stream. The distance from the nozzle to the strip has to match the distance from nozzle to workpiece. This equivalence of distance is important because of the distance variation of peening intensity – as illustrated in fig.2.

The procedures for peening intensity measurement are described in specification J443. This requires the measurement of the deflections induced in a set of Almen strips peened for different time periods. Deflection, as arc height, is plotted as a function of peening time (or the equivalent of time). If the set comprised an infinite number of strips then we would have a continuous "saturation curve" of data points. This is, of course, impracticable and real sets are limited in number, normally to between four and eight

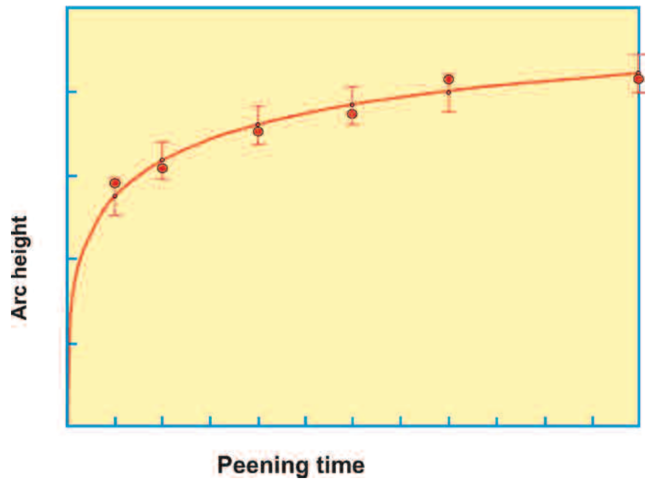

Fig.3 Continuous curve versus a six-point data set.

strips. Fig.3 shows the difference between a continuous curve and a six-point data set. It is important to bear in mind that:

Individual data points, of necessity, have variability

The variability of data points can be represented by error bars – as shown in fig.3. Each error bar indicates the upper and lower limits of "expected values." If the bar limits correspond to one standard deviation on either side of the mean value then two-thirds of values would, on average, lie between the error bars. If on the other hand, they are set at two standard deviations, nineteen out of twenty would, on average, lie between the error bars. In fig.3 the bar limits have been set at two standard deviations. All six values lie between the error bar limits. Hawk-eyed readers may perceive that if the limits had been halved (to one standard deviation) then two of the six points (one in three), would then lie outside the bar limits.

Having obtained a set of data points the next problem is to derive a value for the peening intensity. There are two different methods detailed in J443. We can either (i) use a computer program to analyze the data or (ii) manually select the lowest data point that meets a specification requirement. Both methods are affected by the quality of the data in a given data set. Data that varies from a smooth curve by only small amounts can be categorized as "good" whereas large variations would constitute "bad" data. An important observation is that:

The variation of data from a smooth curve is a measure of the effectiveness of production control.

(1) Computer Analysis

The use of computer analysis to estimate peening intensity has several advantages. These include: **objectivity, uniqueness of intensity value and utilization of every data point.**

Computer analysis is based on (a) fitting the data set to a pre-selected equation and (b) determining the unique point on the corresponding curve that satisfies the criterion that:

Peening intensity is the arc height for which doubling the peening time gives a 10% increase.

For a given fitted curve there is only one point that satisfies this criterion.

Four factors influence the accuracy of computer-analyzed data sets. These are: (i) the data range relative to the unique peening intensity point (ii) the "quality" of the data set (iii) choice of fitting equation and (iv) the number of points in the data set.

(i) Data Range

One important feature of data range is that: "The set must include at least one point having a shorter peening time than that derived for the peening intensity point." The importance of this feature can best be illustrated by an actual example. Consider Data Set No.1 from the eight examples provided by the SAE Sub-committee on Surface Enhancement. Imagine that, instead of the first point, another point had in fact been obtained – 7.1 at a time of 16. The two data sets are shown as Table 1.

Table 1

SAE Test Set No.1 together with Modified set.

SAE TEST SET No.1		MODIFIED SET	
Peening Time	Arc Height	Peening Time	Arc Height
4	6.0		
6	6.9	6	6.9
8	7.0	8	7.0
12	7.0	12	7.0
		16	7.1

Computer analysis, using the French-specified fitting equation, gives the curves shown in fig.4. The SAE Test Set points, 1 to 4, yield a peening intensity of 6.4 at a time of 4.75. For points 2 to 5, on the other hand, the indicated peening intensity is 5.9 at a time of 1.08.

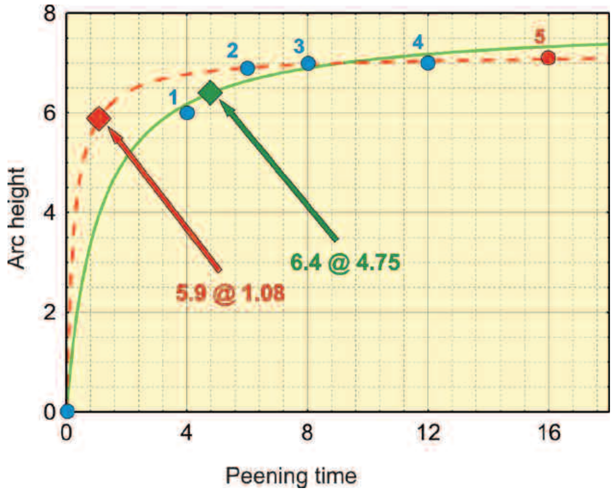

Fig.4 Effect of data set range on derived peening intensity point.

The modified data set has points that lie almost on a straight line. This renders accurate prediction of peening intensity virtually impossible.

A second feature of data range is that "The set must contain a point at a peening time at least twice that of the derived peening intensity time, **T**. This feature is necessary in order to be able to confirm that "Peening intensity is the arc height for which doubling the peening time gives a 10% increase" has been satisfied.

(ii) Quality of Data Set

Every data set will contain, to a greater or lesser extent, variation from a perfectly-smooth saturation curve. It is the amount of variation that defines the quality of the data set. Both random and systematic variations of measured arc heights are inevitable. The greater the number of points in a data set the easier it is to cope with these variations. If, however, the total variation is excessive then any form of data analysis becomes very difficult. The idiom "You cannot make a silk purse out of a sow's ear" becomes appropriate. A decision has to made as to whether or not a data set is of acceptable quality. A subjective approach is to make a "commonsense" judgment - based on a visual inspection of plotted data points and the corresponding best-fitted curve. Objective approaches can be based on the closeness of fit of the data set i.e. the "sum of squares."

(iii) Choice of Fitting Equation

The choice of fitting equation (if choice is available) should be based on the number, range and quality of data points in any given set and whether or not a multi-fixture setup is involved. For the "Solver Suite" a rough guide would be (a) to use either EXP2P or 2PF programs for single-fixture situations with either four or five medium-to-good-quality points in each set (the wider the range of points the more likely it is that 2PF would be the better choice); (b) to use 2PF for multi-fixture situations with either four or five medium-to-good points in each set and (c) to use EXP3P for six or more points in each set.

(iv) Number of Points in the data set

It is not generally recognized that:

The precision of the derived peening intensity depends on the number of points in the data set

As an approximation, the error band for computer-derived peening intensity is equal to the error band for individual points divided by the number of points in the set. For example, if the individual data point error band width averages at 1.0 units for a set of five data points then the peening intensity error band width will be only 0.2 units (1.0/5). It follows that the larger the number points in a data set the more accurate will be the derived peening intensity.

(2) Lowest Data Point Selection

There are some situations that preclude the possibility of obtaining a complete saturation curve. These occur when a single pass (stroke or table rotation) gives an arc height close to the maximum given by repeated passes. Arc heights versus passes then appear as illustrated by fig.5. The peening intensity, **H**, is then defined as "the lowest data point for which arc height increases by no more than 10% when the peening exposure is doubled."

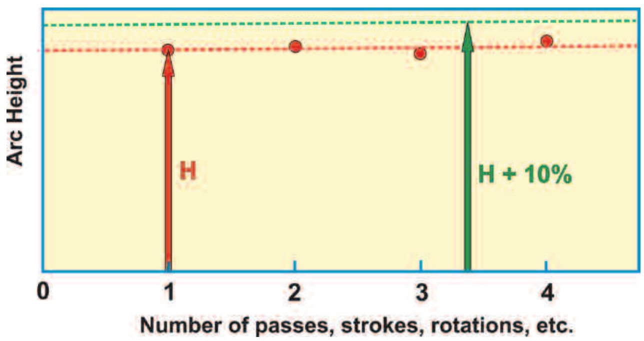

Fig.5 Lowest data point for which arc height increases by no more than 10% when peening exposure is doubled.

The type of data point range in fig.5 is similar to that of the "modified set" shown in fig.4. It would therefore be inappropriate to attempt to apply a curve-fitting procedure. Peening intensities obtained using "lowest point selection" will be higher than those that would have been obtained if computer analysis of a saturation curve had been possible. The difference will be approximately 10%. Another significant factor is that the declared peening intensity value is now that of a single data point.

VERIFICATION

Peening is generally carried using an integral number of passes/strokes/table rotations. During setup one strip is peened for each of the several passes. The resulting data set is then used to produce a saturation curve. That curve is then analyzed to confirm that a satisfactory peening intensity has been achieved. This occurs at a derived time, **T**.

Considerable time and effort is expended in order to establish the machine settings that will yield peening intensities that fall within the specified tolerance band at the peening intensity time, **T**, – as is shown in fig.6. Having established those settings it is necessary to verify, periodically, that those settings continue to provide consistent arc height responses. These responses are not, however, the same as peening intensities. Verification for situations involving a single Almen strip holder is relatively simple - when compared with that for setups that might involve several holders.

Single Holder Verification

Verification of intensity is described in the SAE Specification J443. Single strip exposure is allowed when a single holder is involved. This strip should, ideally, be exposed for the time, **T**, of the peening intensity point. It is pointed out that this is not feasible when integral numbers of passes/rotations are being used. Peening intensity times are, however, rarely integers, see fig.6. J443 states that "the nearest practicable time to T should then be used. The arc heights obtained must repeat the value from the saturation curve +/-0.038mm…" The "value from the saturation curve" can be obtained automatically by employing a simple add-on to any Curve Solver program. This add-on substitutes the selected integral 'time' value into the fitted equation to yield the corresponding arc height. This arc height might properly be called the "target verification arc height." It is not a peening intensity value. As with the derived peening intensity the precision of a saturation curve derived point is more precise than that of individual data points. A derived target verification arc height is shown in fig.6. J443 requires that a single repeat exposure matches the target verification arc height to within

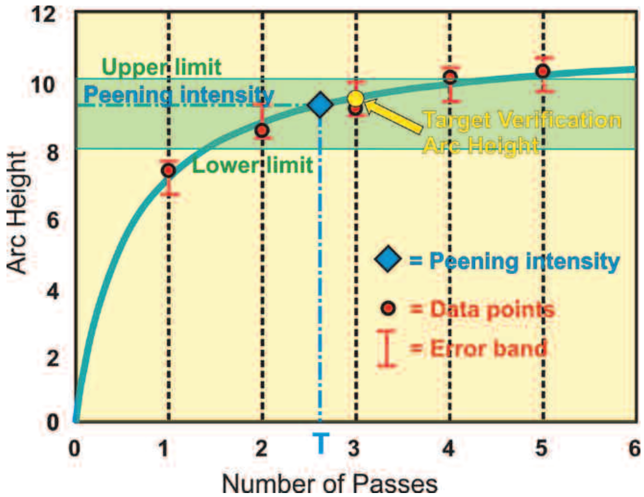

Fig.6 Peening Intensity and Target Verification Arc Height derived from data points having integral "time" values.

+/- 0.0015" (+/-0.038mm). As an alternative, there is a simple procedure for adjusting the specification limits (upper and lower) to allow for the "time" difference between **T** and the selected integral verification "time." This involves using the ratio of the target verification/peening intensity arc heights. Adjustment is achieved by simply multiplying the upper and lower limits by the calculated ratio. The following example serves to show how such adjustment could be applied in practice.

Example of Verification and Limit Adjustment for a Single-Holder Situation

The example, illustrated in fig.7, is based on applying the Curve Solver 2PF program to SAE Data set No.4. This yielded values of: a = 6.22 and b = 0.58 for the fitting equation h =a*t/(b + t) giving a peening intensity of 5.09 at a time of 2.62. Substituting 3 (for t) into the 2PF equation so that h = 6.22*3/(3 + 0.58) gives the "target verification intensity" to be h = 5.21. Multiplying specified tolerance values (4 and 6) by 5.21/5.09 gives 4.1 and 6.1 as revised limits. Verification is achieved by peening for a "time" of 3 passes and requiring that the arc height lies between 4.1 and 6.1 (shown as green bars in fig.7). For this particular example adjustment of the tolerance band is so small that it does not affect the verification outcome. Instances where the peening intensity point is much closer to a tolerance limit would, however, benefit from adjustment of that limit.

Multiple Holder Verification

Using multiple holders on a fixture will produce multiple "saturation times," **T**. J443 recommends that a single verification exposure time be used in these situations and that "The time selected should be not less than the shortest saturation time nor greater than the longest saturation time of the group of holders. The resulting arc height readings must then repeat the value achieved in the original saturation curve +/-0.038mm (+/- 0.0015")."

An objective alternative (to the J443 recommendation) is to average the several peening intensity times and use the rounded-up integral value of that average. Verification can then carried out by exposing one strip at each of the fixtures for that "rounded-up integral time." The requirement for target verification arc height at each holder can be assessed in a similar way to that described previously for single-holder situations. A secondary problem is to be able to visualize the large amount of data that is involved.

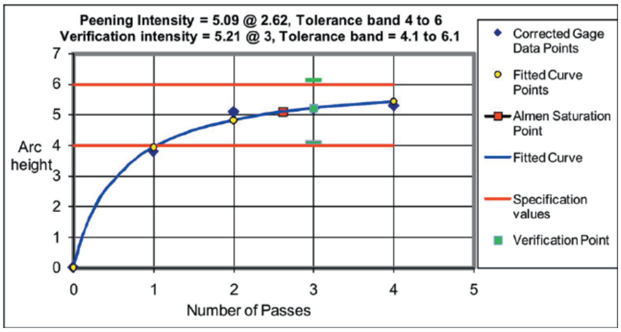

Fig.7 Verification procedure for SAE Data Set 4 using 2PF Solver program.

A simple computer program, based on Excel, has been devised that carries out all of the corresponding calculations automatically. The program also produces adjusted upper and lower tolerance limits. These could be used as an alternative to the "+/- 0.0015" requirement. The following example serves to show how the program could be applied in practice.

Example of Verification Procedure for a Multi-Holder Situation

For this example, it is assumed that the setup involves seven Almen strip fixtures. Saturation curves are produced for each fixture and analyzed using the Solver 2PF program. The corresponding derived peening intensities and times are shown in fig.8 and manipulated using the Excel-based "Verification Program." The average of the seven peening intensity times, **T**, is **5.71** which rounds up to **6**. Lower and upper limits of **8** and **10** have also been assumed. Separate adjustments for **T = 6** are made to these limits (as described for the single-holder situation) for each fixture. The target verification arc height values (obtained by substituting **T = 6** into each saturation curve equation) are generated in the yellow column.

One strip at each of the seven fixtures is simultaneously peened for **T = 6**. The corresponding measured "verification arc heights" are entered in the blue column. Each value is required to lie between the adjusted lower and upper limits.

The differences between the verification and target arc heights are calculated and shown in the "Change" column. In order to simulate a "problem situation" the verification arc height values have been deliberately inflated - relative to the previous saturation curve arc height measurements at T = 6. The deliberate inflation shows up as a preponderance of "PLUS" values in the Change column. This preponderance would rarely occur randomly and is therefore indicative of a change in one or more of the control variables (such as air pressure or wheel speed). The final column shows, clearly, that all seven verification strips satisfy the adjusted tolerance band limits.

Two-strip Intensity Verification

<u>One-strip verification cannot show that the shot stream's intensity is being maintained</u>. It simply confirms that the arc height response at a particular location is consistent. The situation is illustrated by fig.9 which contains the saturation curve of fig.7 together with two other curves. A target verification arc height at an integral peening time, **T_{NT}**, of 3 is indicated. Three saturation curves, having peening intensities shown at 1, 2 and 3, all pass through the same target verification arc height of 5.21. Two-strip testing will, obviously, differentiate between the three curves This is normally based on running the second strip

Fixture No.	Peening Intensity	T	Target Verification Height at Roundup	Verification Arc Height at Roundup	Change		Adj. Lower	Adj. Upper	Verification O.K.
1	8.2	6.00	8.2	8.8	0.6	PLUS	8.0	10.0	YES
2	8.7	6.80	8.5	8.6	0.11	PLUS	7.8	9.8	YES
3	9.0	6.80	8.8	8.9	0.11	PLUS	7.8	9.8	YES
4	9.2	5.00	9.5	8.7	-0.8	MINUS	8.3	10.3	YES
5	9.4	2.40	10.6	10.8	0.25	PLUS	9.0	11.2	YES
6	8.3	7.00	8.1	8.2	0.14	PLUS	7.8	9.7	YES
7	8.4	6.00	8.4	8.7	0.3	PLUS	8.0	10.0	YES

Average T = 5.71
Roundup = 6.00

Lower Specification Limit = 8
Upper Specification Limit = 10

Fig.8 Solver 2PF Verification Program applied to a seven-holder setup.

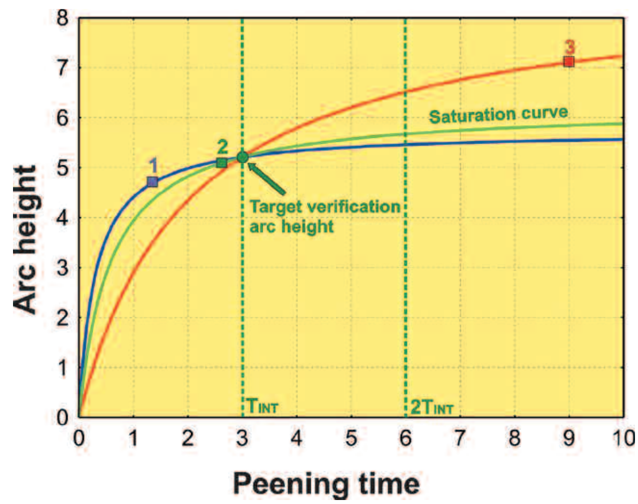

Fig.9 Alternatives to original saturation curve yielding identical target verification arc heights.

at **$2T_{INT}$** - twice **T_{INT}**. Two-strip tests therefore provide some degree of intensity verification.

It is worth noting that large changes of shot flow rate and shot velocity would be needed to change the peening intensities by the amounts shown in fig.9. Such large changes would not normally be encountered, but could arise if something drastic has happened to the control system.

SUMMARY

Peening intensity is the <u>potential</u> ability of a shot stream to induce a given depth of compressed, plastically-deformed, surface material. This potential ability is only realized when the component has been peened. It is important to appreciate that peening intensity varies with distance from the source of shot acceleration.

Quantification of peening intensity is achieved by measuring and analyzing the arc heights of a set of Almen strips - each peened for a different time. Plotted arc heights <u>approximate</u> to a continuous curve. Each data set can be objectively analyzed by using readily-available computer programs. The range (of peening times), quality of data points, number of data points and choice of fitting equation are important factors in achieving effective quantification.

Specification of the required peening intensity is normally based on a permitted range of arc heights at a derived, non-integral, peening time, **T**.

Verification with an integral number of passes involves target verification arc heights derived from the saturation curves. An objective Excel-based "Verification Program" is available that carries out all of the required calculations automatically. This is particularly useful if several holders are involved for a given fixture. Two-strip testing provides some degree of actual intensity verification.