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December 2009

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Introduction

The release of NASA-STD-5009,[1] "Nondestructive Evaluation Requirements for Fracture Critical Metallic Components," in April 2008 overturned the long standing requirement that either sensitivity Level 3 or Level 4 liquid penetrants could be used for NASA Standard Level liquid penetrant inspections. The new requirement imposed by NASA-STD-5009 states that: "The penetrant system used shall be a fluorescent penetrant of Level 4 sensitivity." The ostensible rationale for this change was that the liquid penetrant capability studies performed in the 1970s, which are the basis for the NASA Standard Level crack sizes in NASA-STD-5009, were based on tests conducted with penetrants that were deemed to be equivalent to the modern day sensitivity Level 4 designation.

The requirement that only sensitivity Level 4 penetrants can be used for NASA Standard Level NDE created an uproar from many NASA contractors who complained about the cost of switching penetrant materials and developing new procedures, or having to perform demonstration tests with existing sensitivity Level 3 penetrants in order to qualify them for use. To address the issue, the NASA Nondestructive Evaluation Program funded a task in October 2008 to compare the performance of sensitivity Level 3 and Level 4 penetrants. This NASA Technical Memorandum documents the results from the study.

Penetrant Inspection Materials

The penetrants selected for the study were Method A, Water Washable and Method D, Post Emulsifiable, Hydrophilic, as these are the most common penetrant inspection methods used in the aerospace industry. Sensitivity Level 3 and Level 4 penetrants from two manufactures, Sherwin and Magnaflux, were selected. Table 1 shows the matrix of penetrant inspection materials used in the study. Note that the same nonaqueous developer (Sherwin D-100) was used for all the Method A inspections and likewise a consistent dry powder developer (Magnaflux ZP-4B) was used for the Method D inspections.

Method	Sensitivity Level	Penetrant	Remover	Developer
A	3	Magnaflux ZL-67	N/A	Sherwin D-100
A	4	Magnaflux ZL-56	N/A	Sherwin D-100
A	3	Sherwin HM-607	N/A	Sherwin D-100
A	4	Sherwin HM-704	N/A	Sherwin D-100
D	3	Magnaflux ZL-27A	Magnaflux ZR-10B	Magnaflux ZP-4B
D	4	Magnaflux ZL-37	Magnaflux ZR-10B	Magnaflux ZP-4B
D	3	Sherwin RC-65	Sherwin ER-83A	Magnaflux ZP-4B
D	4	Sherwin RC-77	Sherwin ER-83A	Magnaflux ZP-4B

Table 1: Summary of the penetrant materials used in this study.

Procedures

Seven of the eight inspectors that participated in the study were at a vendor local to NASA Goddard Space Flight Center (GSFC). The remaining inspector was a member of the GSFC Materials Engineering Branch. First, four vendor inspectors and the GSFC inspector completed the Method A test matrix. Two of the vendor inspectors that completed the Method A matrix then also completed the Method D matrix. The GSFC inspector also completed both matrices. Three vendor inspectors that did not complete the Method A matrix completed the Method D matrix. Hence, six inspectors completed demonstration tests using the Method D matrix.

Method A Procedure

For the Method A inspections, the vendor's procedure was utilized by all the inspectors including the GSFC inspector. The minimum penetrant dwell time was 20 minutes and the developer time was 10 minutes. All the other parameters, i.e., wash pressure, wash temperature and drying oven temperature were within established limits. Quality assurance checks for black lights, background lighting, etc. were in place and maintained. As important, all these parameters were constant throughout the test matrix.

Each inspector progressed through the matrix of four Method A penetrants with no knowledge of the actual penetrant being used. The order in which a particular inspector progressed through the penetrants was varied. In addition, the inspectors were given no feed back about their performance until the study was complete. Inspectors were typically tested once a week and due to scheduling there were often several week delays between a single inspector taking the test. A total of five inspectors completed demonstration tests using the matrix of four Method A penetrants.

Method D Procedure

The vendor did not address Method D in their penetrant procedure, as this is not a technique they typically use because of the quality assurance checks on the emulsifier. As a consequence, GSFC introduced a procedure for this process. The minimum penetrant dwell time was 30 minutes, the emulsifier concentration for both the Magnaflux ZR-10B and the Sherwin ER-83A was 16.7 percent by volume (one gallon of emulsifier mixed with five gallons of water) and the emulsification time was 2 minutes. Specimens were prewashed prior to emulsification, however there was no established limit on the prewash or post wash times. After oven drying, the dry powder developer was applied by a manual dip and drag technique and there was no minimum developer time. All other parameters (wash pressure, oven temperature, etc.) were the same as those used in the vendor procedure for Method A. Again, the sequence that an inspector progressed through the matrix of penetrants was varied and no performance feed back was supplied.

Crack Panels

The crack panels used in the study were 6061 aluminum and have dimensions of approximate 8 by 3.5 by 0.25 inches thick. The panels contain low cycle fatigue cracks with aspect ratios (crack depth divided by crack length) of approximately 0.3. The cracks were grown using a Fatigue Dynamics Inc. Model LFE-500 Life, Fatigue and Endurance Testing Machine (see Figure 1). This testing machine was setup to induce tension-tension fatigue in bending with maximum tensile stresses of approximately 35,000 pounds per square inch. The starter notch for the crack growth consisted of three closely spaced and aligned 0.025 inch diameter holes that were 0.020 inch deep. Figure 2 shows an optical photograph of a fatigue crack broken open showing the aspect ratio achieved by this configuration. The starter holes were removed using a fly cut and the panels were etched in a sodium hydroxide solution to remove metal smear.

The overall set of panels used in the study contains 82 cracks with lengths ranging from 0.023 to 0.215 inches. The majority of the crack lengths are close to 0.050 inches, as a portion of the panel set is used to qualify inspectors for the NASA Special Level penetrant inspection crack length of 0.050 inches. The distribution of crack lengths is shown in Figure 3. The cracks are all on one side only of the panels and the inspectors are asked only to inspect this one side. This approach was adopted to minimize the amount of scratching and other handling damage that occurs during demonstration testing, as the non crack side of the panel can be placed on any surface with out concern for the panel condition. This policy has helped extend the useful life of the panels.

Figure 1: Photograph of the Fatigue Dynamics Inc. Model LFE-500 Life, Fatigue and Endurance Testing Machine with a 0.25 thick aluminum plate in bending.

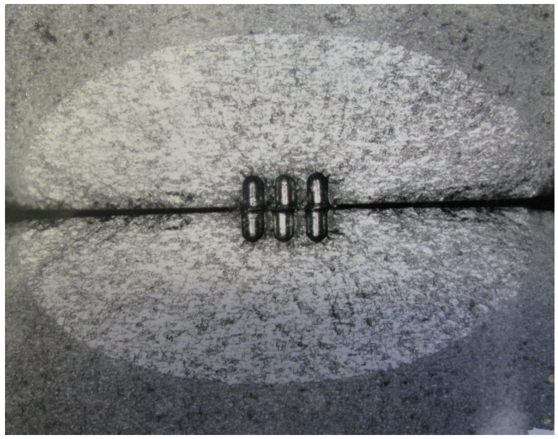

Figure 2: Optical photograph of a fatigue crack which was broken open to reveal the crack aspect ratio. The two halves of the specimen have been placed back-to-back. The surface crack length for this crack was approximately 0.32 inches.

The inspectors were typically given a set of 30 panels with a total of 79 to 82 cracks. One or two of the panels in the set were blank, i.e., contained no cracks. The inspectors are provided with an inspection grid with 3/8 inch squares and asked to record all crack locations as a function of grid location (see Figure 4). The actual hits (correct crack finds), misses (missed cracks) and false calls (erroneous crack finds) were then tabulated based on the inspector's list of crack locations.

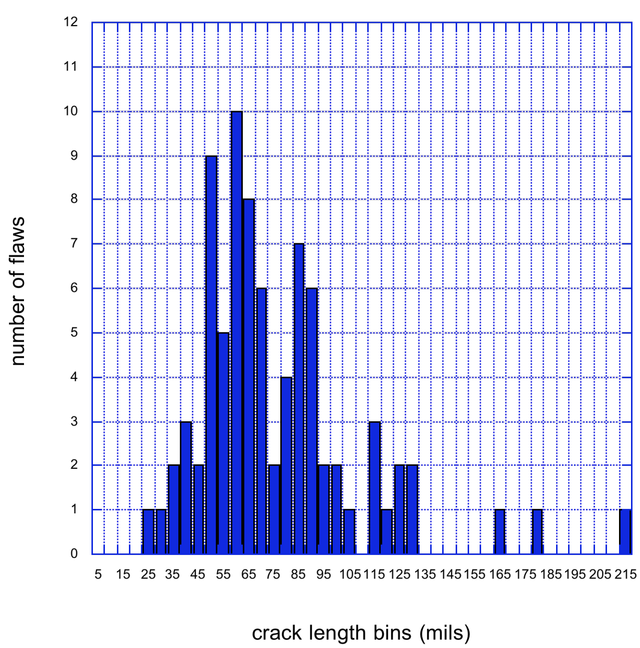

Figure 3: Distribution of crack lengths binned by 0.005 inches (5 mils) for the entire 82 flaws in the aluminum panel set.

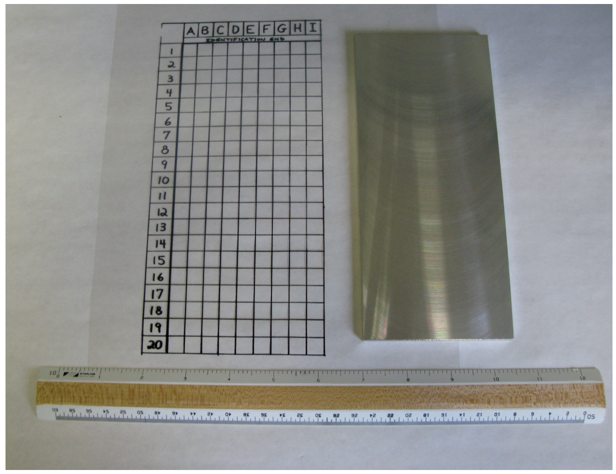

Figure 4: Optical photograph of an aluminum crack panel and the grid used to identify the detected crack locations.

Data Analysis

The hit-miss data from each demonstration test was analyzed using two different approaches to yield a crack length that corresponds to detection with 90 percent reliability and 95 percent confidence (a90/95). The first technique was a point estimate technique, which is based on binominal distribution statistics. The second method is a curve fit method based on the Logit model.

Point Estimate Method

Usually, the point estimate method is applied to a set of cracks with a narrow range of sizes. For example, NASA uses this technique to qualify inspectors for the NASA Special Level penetrant inspection crack length of 0.050 inches. During such a demonstration test, the inspector is given a set of crack panels that ideally contains 29 cracks of exactly 0.050 inches length. Because of the difficulty in controlling the crack length during panel production, the 29 cracks typically have a range of 0.045 to 0.055 inches (plus or minus 10 percent). Based on the binomial statistics, if the inspector finds all 29 cracks, then an a90/95 at 0.050 inches has been demonstrated. Volume 11 of the Metals Handbook 8th Edition[2] gives an excellent explanation of the statistics used by the point estimate method.

Another outcome of the panel production process, is that in order to get 29 cracks within the desired length range, one usually ends up with a significant number of cracks both smaller and larger than the desired range. This is a consequence of the fact that many panels in a set contain more than one crack. If a panel ends up with any crack within the desired range it will probably be included in the set even if it has both cracks larger and smaller than the desired range. This is the reason the set of GSFC aluminum panels has the wide range of crack lengths seen in Figure 3.

During a NASA Special Level demonstration test with a panel set containing 29 cracks in the target range of 0.050 inches and with both some larger and smaller cracks, the inspector successfully demonstrates an a90/95 of 0.050 inches if they find all 29 cracks in the target range as well as all the larger cracks. There is no penalty for missing cracks smaller than the target range.

In the case of the demonstration tests in this study, there is not a requirement that an inspector demonstrates an a90/95 of 0.050 inches. On the contrary, we are interested in seeing at what length a90/95 is successfully demonstrated and then comparing this demonstrated length for the different sensitivity Level penetrants. The implementation of the point estimate in this context requires finding a group of 29 cracks that are found where all the cracks with lengths above the range of these 29 cracks are also found. The demonstrated size is then considered to be the largest crack length in the set of 29 flaws (not the average).

The hit-miss data set is also evaluated to look for sequences of flaws that meet the other a90/95 hit-miss combinations identified in the Metals Handbook article[2], i.e., 45 hits for 46 cracks, 59 hits for 61 cracks and 72 hits for 75 cracks. Again there is the consideration that all of the cracks larger than the identified set must also be correctly hit or found. The combination that yields the lowest a90/95 is the reported number.

Curve Fit Technique

In this study, the curve fit technique is used only to compare the results between different penetrant sensitivity Levels or inspectors and is not used to quantify or demonstrate NASA Special Level capability.

If using the point estimate method to assess the capability of a nondestructive evaluation technique (instead of simply demonstrating a90/95 at a single crack length), then one would ideally have a set of panels with 29 cracks in each of a range of crack lengths. Well-trained inspectors using sound techniques pass point estimate penetrant inspection demonstration tests at crack lengths of 0.050 inches (the NASA Special Level crack length). However, not all inspectors pass the 0.050 inch demonstration test while on the other hand some inspectors not only find the 29 cracks in the 0.050 inch set but they also find the majority of the smaller cracks in the set. If it is desired to know exactly how well an inspector could perform, then we would potentially have a crack panel set with 29 cracks at each length of 0.075, 0.070, 0.065, 0.60, 0.055, 0.050, 0.045, 0.040, 0.035, 0.030, and 0.025 inches (or some similar distribution). This set would have over 300 cracks and the time and cost to produce as well as inspect such a set of panels is prohibitive.

In order to overcome this problem, statisticians have proposed numerous models such as the log normal distribution function, log-logistics (also referred to as the log odds) functions and Probit and Logit models to fit hit-miss inspection data. The statisticians recognized that most nondestructive inspection techniques produce a situation where below a certain crack length almost all of the cracks are missed and above a slightly larger crack length almost all of the cracks are hit. In this case, a plot of the probability of detection (POD) as a function of the crack length (or the log of the crack length) yields a characteristic "S" shape curve. This "S" shaped curve can be well fit by the various models mentioned above to yield an a90/95 crack size. This approach is explained in detail in Volume 17 of the Metal Handbook 9th Edition[3] for the log normal distribution and the log-logistics function. The statistics book by J.A. Cramer gives a full explanation of the Probit and Logit models.[4]

The hit-miss inspection results generated in this study for the most part (43 out of 44 cases) produce "S" shaped curves and hence using a curve fit technique to analyze the data is appropriate. In the one case where data did not conform to the curve fit technique, the inspector missed only one crack out of 82, however the crack length was 0.070 inches and hence was near the center of the distribution of lengths.

The curve fit technique adds value to this study because it allows for the evaluation of combination hit-miss data sets, i.e., all Method A sensitivity Level 3 hit-miss results versus all Method A sensitivity Level 4 results. The use of the point estimate method to evaluate such data sets can produce misleading results. For example, if one of the five inspectors performing the Method A inspections during a particular inspection missed a very large crack when using one of the sensitivity Level 3 penetrants, and if we were to combine the hit-miss data from all five inspectors into a single data set, the overall point estimate a90/95 would be determined by this one inspector's result (a consequence of the point estimate method is that the a90/95 will never be smaller than the largest missed crack length). On the other hand, the overall data set would have the characteristic "S" shape and evaluation of the data set using the curve fit technique would not produce a result dominated by a single inspection, yet still would include the results from all inspectors.

In support of an effort to update MIL-HDBK-1823[5], Charles Annis developed a R (an open source mathematics software program for statistical computing and analysis) package titled "mh1823 POD." The menu driven package uses R commands for all data manipulation , statistical analysis and graphics. For hit-miss data, the package offers the user eight different curve fit options all of which are appropriate models for studies were the response or outcome is binary, i.e., a crack is hit (1) or missed (0). Four of the models are based on the log of the crack length and four are not. Each is based on a link to an existing R function, e.g., logit, probit, loglog or cloglog. For each of the eight models, the package provides a deviance value which is a measure of the goodness of fit. For this study, the Logit link using the log of the crack length was selected for all the data set analyses, as the deviance for this choice was generally the lowest. Note that for the data sets in this study all the model options produced similar a90/95 results. For example, a Method A inspection with 77 hits and 4 misses was fitted using the eight possible links and the a90/95 values ranged from 0.052 to 0.055 inches (the deviance values ranged from 13 to 15).

Note again that in this study we are not using the curve fit technique to quantitatively measure the capability of penetrant inspections and we are not attempting to determine which model should be used. Here, a single curve fit technique (Logit) is universally applied to compare results from different penetrants or inspectors. We state this because the point estimate method is a more conservative technique for quantifying a90/95 and is the approach preferred by NASA for demonstrating capability at a single crack length.

False Calls

False calls were not included in the analysis of the data. The tables in the results section do include the number of false calls for each inspection. The grid provided for locating crack indications has 90 cells, hence for a demonstration test with 30 panels and a one sided inspection there are 2700 possible crack locations. The inspectors were instructed to identify only "crack like" indications, however they were given no feedback about their false call rates between inspections.

Results

Method A Results

Table 2 contains all of the individual Method A inspection results. The first vendor inspector (Vendor 1) to go through the matrix of tests was given 23 to 26 crack panels with 59 to 66 cracks. With this number of cracks, there was not a point estimate method solution for two of the four trials. As a consequence, additional crack panels were added to set to increase the number of larger cracks for all subsequent inspectors.

Point estimate analysis for the remaining four inspectors with 81 to 82 total cracks produced a solution in all cases. As mentioned in the Data Analysis section, there was one trial where the Logit curve fit technique did not produce a solution. This was the case for the Vendor 3 inspector using Sherwin HM-704 where the one crack missed was 0.070 inches long.

Table 3 provides a comparison of the sensitivity Level 3 versus the Level 4 penetrants. The table shows that the total percentage of cracks found for the 10 trials with each sensitivity Level of penetrant is essentially identical (92.7 versus 93.0 percent). Likewise the average of the point estimate method a90/95 values for the two sensitivity Levels differ by only 0.003 inches and the average of the Logit curve fit a90/95 values for the two sensitivity Levels differ by only 0.002 inches. The values in the final column of the table were obtained by combining all the sensitivity Level 3 hit-miss data (774 cracks) into a single record and all the Level 4 hit-miss data (775 cracks) in to a single record and then performing Logit curve fits to obtain a90/95 values. With this approach, the a90/95 values for the two sensitivity Level penetrants differ by only 0.001 inches.

Date	Inspector	Penetrant	Sensitivity	Flaws	Hits	Misses	False Calls	a90/95 Logit Curve Fit (inches)	a90/95 Point Estimate (inches)
11/5/08	Vendor 1	HM607	3	59	51	8	0	0.081	N/A
11/12/08	Vendor 1	ZL-56	4	61	56	5	1	0.052	0.063
12/3/08	Vendor 1	HM704	4	63	57	6	0	0.056	0.085
12/10/08	Vendor 1	ZL-67	3	66	59	7	1	0.073	N/A
1/21/09	Vendor 2	ZL-56	4	82	75	7	22	0.061	0.085
1/28/09	Vendor 2	ZL-67	3	81	70	11	15	0.071	0.130
2/4/09	Vendor 2	HM704	4	81	74	7	19	0.059	0.076
2/11/09	Vendor 2	HM607	3	81	75	6	21	0.057	0.080
1/7/09	GSFC 1	HM704	4	82	77	5	8	0.055	0.065
1/14/09	GSFC 1	HM607	3	82	77	5	5	0.056	0.070
1/21/09	GSFC 1	ZL-56	4	82	79	3	3	0.056	0.082
1/28/09	GSFC 1	ZL-67	3	81	78	3	5	0.050	0.062
2/18/09	Vendor 3	HM704	4	81	80	1	7	N/A	0.070
2/25/09	Vendor 3	HM607	3	81	77	4	5	0.054	0.065
3/4/09	Vendor 3	ZL-67	3	81	80	1	9	0.042	0.059
3/11/09	Vendor 3	ZL-56	4	81	80	1	7	0.042	0.059
4/1/09	Vendor 4	HM607	3	81	78	3	9	0.048	0.062
4/15/09	Vendor 4	ZL-67	3	81	73	8	2	0.071	0.090
4/22/09	Vendor 4	ZL-56	4	81	73	8	5	0.061	0.080
4/29/09	Vendor 4	HM704	4	81	70	11	1	0.077	0.130

Table 2: Individual results for each inspector performing Method A demonstration tests.

In order to compare the individual inspectors and the individual penetrants, hit-miss results from individual trials were combined and analyzed using the Logit curve fit technique. Figure 5 shows the a90/95 curve fits for the four different Method A penetrants. Each curve fit was performed on the combined hit-miss data from the five trials (one trial for each of the five inspectors) performed using the penetrant. The a90/95 values for the penetrants range from 0.051 to 0.054 inches.

Sensitivity Level	Number of Trials	Total Number of Flaws	Total Number of Hits	Total Number of Misses	Percent of Flaws Hit	Average Point Estimate a90/95 (inches)	Average Logit Curve Fit a90/95 (inches)	Logit Curve Fit on Combined Hit/Miss Data (inches)
3	10	774	718	56	92.7	0.077*	0.060	0.052
4	10	775	721	54	93.0	0.080	0.058+	0.051

*8 trials
+9 trials

Table 3: Comparison of sensitivity Level 3 versus Level 4 penetrants for Method A demonstration tests.

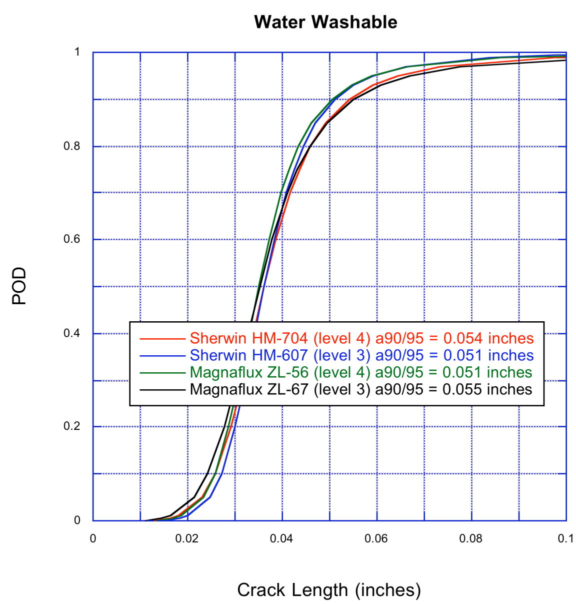

Figure 5: Logit curve fit a90/95 results as a function of Method A penetrant.

In a similar fashion, all of the hit-miss results for each inspector (four trials, two with sensitivity Level 3 and two with sensitivity Level 4 penetrants) were combined and analyzed using the Logit curve fit technique. These results, which are plotted in

Figure 6, show that the demonstrated a90/95 is a stronger function of the inspector than of the penetrant. Here, the a90/95 values varied between 0.041 and 0.058 inches.

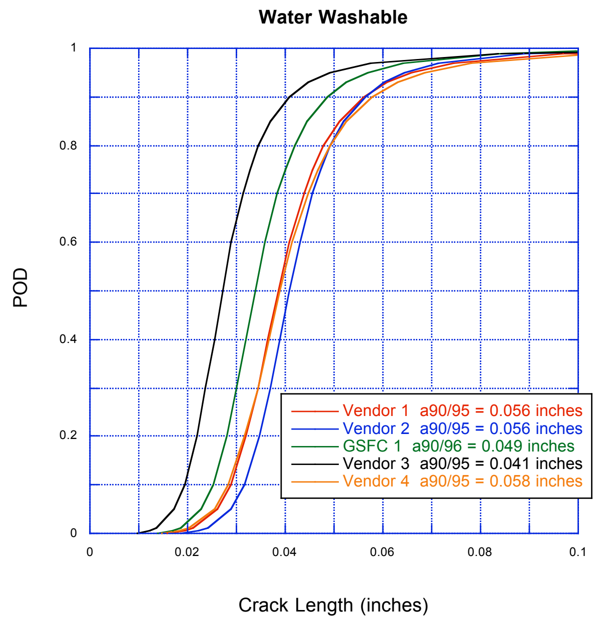

Figure 6: Logit curve fit a90/95 results as a function of Method A inspector.

For the Method A inspections, the largest variable in the process was the application of the nonaqueous Sherwin D-100 developer. One inspector (Vendor 1) applied a heavy coating of the developer (there was no evidence of the aluminum beneath the developer), whereas the remaining inspectors applied lighter coatings. One inspector (Vendor 3) inspected the panels during the development process, i.e., the developer was applied to one crack panel and the panel was immediately observed under the black light. After recording all crack locations, the inspector proceeded to the next panel. The remaining inspectors developed batches of panels and waited at least 10 minutes before beginning the crack identification process.

Method D Results

Table 4 contains all of the inspection results for the Method D process. Point estimate method solutions were obtained for all 24 cases. There were seven cases where no cracks were missed. The Logit curve technique for data sets with all hits and no misses does not yield an a90/95 solution. Switching the smallest crack in the set (0.023 inches) from a hit to a miss yielded an a90/95 solution of 0.026 inches and this is the value reported for the seven cases with no misses.

Table 5 provides a summary of the sensitivity Level 3 versus Level 4 Method D penetrants. The percentage of the total cracks found is slightly higher for the Level 3 penetrants (97.4) versus the Level 4 penetrants (96.1). The average of the point estimate method a90/95 values for the two sensitivity Levels differ by only 0.005 inches and the average of the Logit curve fit a90/95 values for the two sensitivity Levels differ by only 0.007 inches. The values in the final column of the table were obtained by combining all the sensitivity Level 3 hit-miss data into a single record (960 cracks) and all the Level 4 hit-miss data in to a single record and then performing Logit curve fits to obtain a90/95 values. With this approach, the a90/95 values for the two sensitivity Level penetrants differ by only 0.005 inches. In all these cases, the Level 3 penetrants performed better than the Level 4 penetrants.

Date	Inspector	Penetrant	Sensitivity	Flaws	Hits	Misses	False Calls	a90/95 Logit Curve Fit	a90/95 Point Estimate
5/6/09	GSFC 1	ZL-37	4	81	80	1	8	0.044	0.059
5/8/09	GSFC 1	ZL-27A	3	81	81	0	5	0.026	0.058
7/9/09	GSFC 1	RC65	3	81	81	0	2	0.026	0.058
7/10/09	GSFC 1	RC77	4	81	81	0	3	0.026	0.058
5/13/09	Vendor 4	ZL-37	4	81	75	6	1	0.083	0.165
5/20/09	Vendor 4	ZL-27A	3	81	79	2	6	0.05	0.065
8/6/09	Vendor 4	RC65	3	80	72	8	3	0.078	0.165
8/14/09	Vendor 4	RC77	4	80	73	7	11	0.061	0.07
6/2/09	Vendor 3	ZL-27A	3	81	81	0	1	0.026	0.058
6/10/09	Vendor 3	ZL-37	4	80	80	0	0	0.026	0.058
8/25/09	Vendor 3	RC65	3	79	77	2	2	0.052	0.065
9/1/09	Vendor 3	RC77	4	80	79	1	3	0.043	0.059
6/17/09	Vendor 5	ZL-27A	3	79	79	0	16	0.026	0.058
6/30/09	Vendor 5	ZL-37	4	81	75	6	47	0.062	0.09
8/18/09	Vendor 5	RC65	3	80	77	3	3	0.056	0.076
8/20/09	Vendor 5	RC77	4	80	78	2	1	0.05	0.075
6/24/09	Vendor 6	ZL-27A	3	78	78	0	8	0.026	0.058
7/8/09	Vendor 6	ZL-37	4	81	80	1	6	0.026	0.058
7/20/09	Vendor 6	RC65	3	80	77	3	2	0.048	0.062
7/22/09	Vendor 6	RC77	4	81	77	4	2	0.052	0.075
8/13/09	Vendor 7	ZL-27A	3	80	77	3	16	0.058	0.09
8/11/09	Vendor 7	ZL-37	4	80	75	5	30	0.077	0.112
7/25/09	Vendor 7	RC65	3	80	76	4	45	0.059	0.076
7/27/09	Vendor 7	RC77	4	81	76	5	35	0.059	0.07

Table 4: Individual results for each inspector performing Method D demonstration tests.

Sensitivity Level	Number of Trials	Total Number of Flaws	Total Number of Hits	Total Number of Misses	Percent of Flaws Hit	Average Point Estimate a90/95 (inches)	Average Logit Curve Fit a90/95 (inches)	Logit Curve Fit on Combined Hit/Miss Data (inches)
3	12	960	935	25	97.4	0.074	0.044	0.040
4	12	967	929	38	96.1	0.079	0.051	0.045

Table 5: Comparison of sensitivity Level 3 versus Level 4 penetrants for Method D demonstration tests.

In order to compare the different penetrants and inspectors, hit-miss results from individual trials were combined and analyzed using the Logit curve fit technique. Figure 7 shows the a90/95 curve fits for the four different Method D penetrants. Each curve fit was performed on the combined hit-miss data from the six trials (one trial for each of the six inspectors) performed using the penetrant. The plots show that

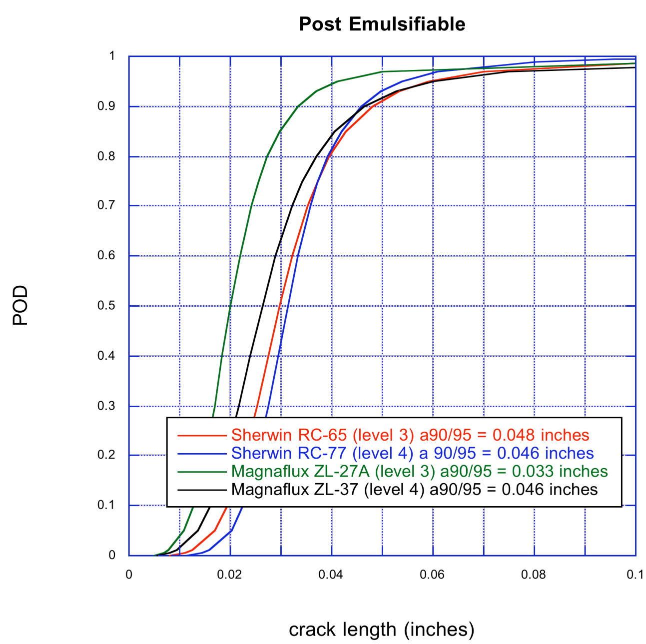

Figure 7: Logit curve fit a90/95 results as a function of Method D penetrant.

one penetrant, Magnaflux ZL-27A, performed better than the remaining three penetrants. Interestingly, this penetrant is sensitivity Level 3. This result is not unprecedented. In a report by John Lively,[6] four of six inspectors who performed penetrant deomonstrations tests using Magnaflux ZL-37 (sensitivity Level 4) and Magnaflux ZL-27A (sensitivity Level 3) performed better with ZL-27A.

Table 6 provides summary results for all four Method D penetrants. This data again shows that the inspectors performed better with ZL-27A and that the remaining three penetrants performed similarly. There was no characteristic of ZL-27A that surfaced during the inspections that would lead one to believe that this penetrant would perform better.

Again, all of the hit-miss results for each inspector (four trials, two with sensitivity Level 3 and two with sensitivity Level 4 penetrants) were combined and analyzed using the Logit curve fit technique. These results, which are plotted in Figure 8, show that the demonstrated a90/95 is again a stronger function of the inspector than of the penetrant. Here, the a90/95 values varied between 0.031 and 0.057 inches, which is similar to the range for the Method A inspectors (0.041 to 0.058 inches). It should also be noted, that the inspector with the largest overall demonstrated a90/95 for Method A, also had the largest a90/95 for Method D.

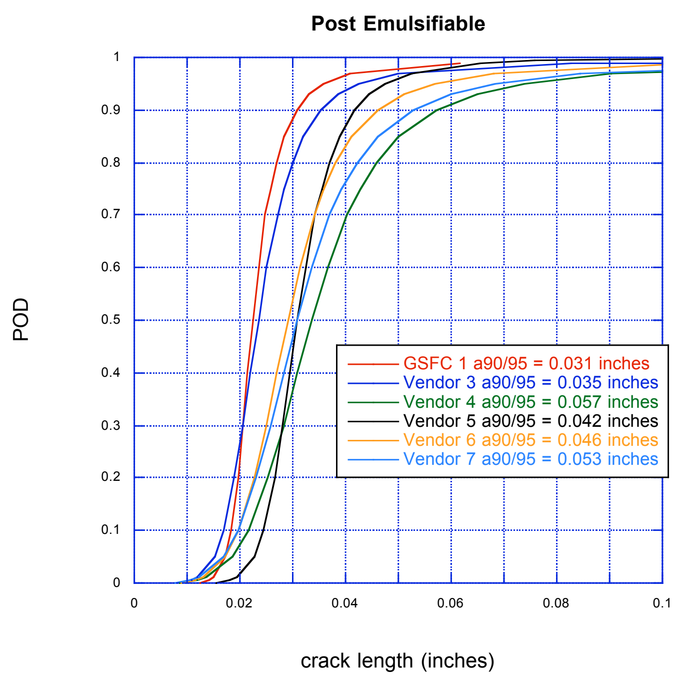

Figure 8: Logit curve fit a90/95 results as a function of Method D inspector.

Penetrant and (Sensitivity Level)	Number of Trials	Total Number of Flaws	Total Number of Hits	Total Number of Misses	Percent of Flaws Hit	Average Point Estimate a90/95 (inches)	Average Logit Curve Fit a90/95 (inches)	Logit Curve Fit on Combined Hit/Miss Data (inches)
Magnaflux ZL-27A (3)	6	480	475	5	99.0	0.064	0.035	0.033
Sherwin RC-65 (3)	6	480	460	20	95.8	0.084	0.053	0.048
Magnaflux ZL-37 (4)	6	484	465	19	96.1	0.090	0.053	0.046
Sherwin RC-77 (4)	6	483	464	19	96.1	0.068	0.049	0.046

Table 6: Comparison of the four Method D penetrants.

Conclusions

For Method A demonstration tests, sensitivity Level 3 and Level 4 penetrants on average produced nearly identical demonstrated a90/95 crack lengths for five different inspectors. For Method D demonstration tests from six inspectors, one sensitivity Level 3 penetrant produced an a90/95 crack length smaller than the remaining Level 3 penetrant and the two Level 4 penetrants. The remaining Level 3 penetrant and the two Level 4 Method D penetrants on average produced nearly identical demonstrated a90/95 crack lengths. The a90/95 demonstrated crack lengths for individual inspectors varied more than for individual penetrants, i.e., the dominant factor in the demonstrated a90/95 is the inspector, not the penetrant.

Only two of the 44 demonstration tests in the study produced point estimate a90/95 crack lengths greater than 0.150 inches long (the NASA Standard Level penetrant crack length). These two results were from the same inspector, one with a Method D sensitivity Level 3 penetrant and one with a Method D sensitivity Level 4 penetrant.

The results from both the Method A and Method D demonstration tests strongly support the conclusion that sensitivity Level 3 penetrants are acceptable for NASA Standard Level penetrant inspections.

References:

[1]NASA-STD-5009, "Nondestructive Evaluation Requirements for Fracture-Critical Metallic Components," Baseline Release, April, 2008.

[2]P.F. Packman et al., "Reliability of Flaw Detection by Nondestructive Inspection," Metals Handbook, 8th Edition, Volume 11, 1976.

[3]A.P. Berens, "NDE Reliability Data Analysis," Metals Handbook, 9th Edition, Volume 17, 1989.

[4]J.S. Cramer, Logit Models from Economics and Other Fields, Cambridge University Press, 2003.

[5]MIL-HDBK-1823A, "Nondestructive Evaluation System Reliability Assessment," April 7, 2009.

[6]J.A. Lively and T.L. Aljundi, "Fluorescent Penetrant Inspection Probability of Detection Demonstration Performed for Space Propulsion," AIP Conf. Proc., Vol. 657, Issue 1, 2003.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

Historically both sensitivity level 3 and sensitivity level 4 fluorescent penetrants have been used to perform NASA Standard Level inspections of aerospace hardware. In April 2008, NASA-STD-5009 established a requirement that only sensitivity level 4 penetrants were acceptable for inspections of NASA hardware. Having NASA contractors change existing processes or perform demonstration tests to certify sensitivity level 3 penetrants posed a potentially huge cost to the Agency. This study was conducted to directly compare the probability of detection sensitivity level 3 and level 4 penetrants using both Method A and Method D inspection processes. The study results strongly support the conclusion that sensitivity level 3 penetrants are acceptable for NASA Standard Level inspections.

15. SUBJECT TERMS

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