Results of Data Matrix Barcode Testing for Field Applications

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Abstract:

For the last few years, researchers at Oak Ridge National Laboratory have been investigating direct-part-marking techniques and barcode specifications that may be applicable for UF_6 cylinders. Testing in 2016 and 2017 evaluated how the size of the barcode, read distance, read angle, surface finish of the material, and marking technique impacted barcode readability as measured by commercial off-the-shelf barcode readers. This work recommended a specific combination that was integrated into the 2017 World Nuclear Transport Institute "Standard for UF_6 Cylinder Identification." Parts of the recommendation, such as the suggestion to use laser etching with laser marking ink, were not previously systematically tested to ensure they would remain useful over a cylinder's entire lifespan. This paper discusses selected qualitative and quantitative results from accelerated environmental testing that tries to confirm that the marking ink and other characteristics of the recommendations would survive the environmental conditions UF_6 cylinders often experience.

Keywords: global identifier; UF_6 cylinder; unique identifier

1. Introduction

Staff at Oak Ridge National Laboratory (ORNL) have been evaluating machine-readable features to enhance safeguards for UF_6 cylinders for several years. As reported in the 2017 Institute of Nuclear Materials Management (INMM) paper by Garner et al. [1], the barcode size and marking technique can impact the range over which commercial off-the-shelf barcode readers can successfully decode barcodes. The 2017 INMM paper concluded that a 1.4 in. Data Matrix barcode laser etched with CerMark laser marking ink onto a ball blasted-stainless-steel plate would be very suitable for representative use cases involving a UF_6 cylinder global identifier. These recommendations were subsequently incorporated into the 2017 World Nuclear Transport Institute (WNTI) "Standard for UF_6 Cylinder Identification" [2].

This earlier work focused on Data Matrix two-dimensional (2D) barcodes. Data Matrix and QR (Quick Response) are two of the most widely used 2D barcode symbologies and can be printed on labels or directly marked on parts. The contrast and other characteristics these 2D barcodes are covered by several standards:

- ISO/IEC 16022, "Data Matrix bar code symbology specification"
- ISO/IEC 18004, "QR code bar code symbology specification"
- ISO/IEC 15415, "2-D bar code print quality standard," which incorporated and expanded upon marking quality definitions from ISO/IEC 16022 and ISO/IEC 18004
- AIM DPM-1-2006, verification standard for direct-part-marketing (DPM) 2D code image quality established by the Automatic Identification Manufacturers based on ISO/IEC 15415:2004
- ISO/IEC TR 29158, verification standard for DPM 2D code image quality adopted by International Organization for Standardization, which was based on AIM DPM-1-2006 and incorporated ISO/IEC15415:2011

Figure 1 illustrates the relationship between the standards that govern 2D barcodes. Data Matrix barcodes are considered better than QR codes for industrial applications because they have higher error correction. Many 2D barcode symbologies include error correction. The 14 x 14 module Data Matrix barcodes as recommended by WNTI include 28 to 39% error correction [3]. QR codes have four error correction levels but top out at 30% error correction.

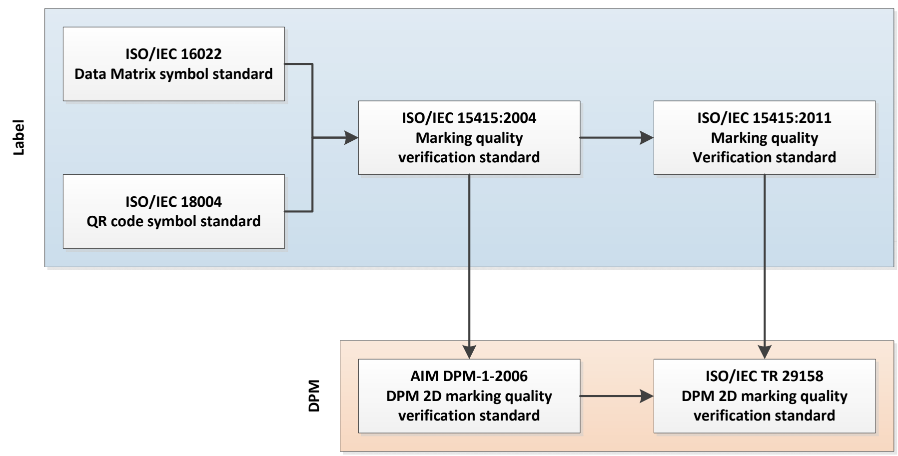

Figure 1: Multiple standards apply to 2D barcodes and barcode verification.

2. Samples for Accelerated Environmental Testing

In 2018 and early 2019 ORNL collected approximately 630 samples of the following types:

- Chemically etched stainless steel samples
- Laser-etched stainless steel samples
- CerMark-coated laser-etched stainless steel samples
- Laser-etched Tesa tape samples advertised to be as robust as metal once applied to a substrate
- Rebo premium vinyl labels
- Zebra Z-Ultimate 3000T
- Zebra Z-Endure 4000T advertised to offer 10-year outdoor durability

Most of these samples were welded, epoxied, or adhered to ½ in. thick A516 steel. This is the same alloy and thickness used to make model 30B UF_6 cylinders. The ORNL vendor supplied 4 ft x 8 ft A516 sheets with a mill finish. ORNL machinists laser-cut the large sheets to 3 in. x 6 in. coupons. The ORNL machinists then sandblasted the samples. Sandblasting did not sufficiently remove the mill finish for welding, so the coupons for the welded samples were all polished before welding.

Some of the stainless steel samples (chemically etched, laser etched, and CerMark-coated laser etched) were adhered to the A516 coupons using Aremco 517 epoxy. This epoxy has been used by other UF_6 industry members to adhere new placards to the skirt of cylinders. This type of epoxy may be an attractive alternative for industry compared to welding because it may be a permanent way to adhere the global identifier to the front face of UF_6 cylinders without requiring an R-stamp welder during the recertification process. Some of these samples were epoxied to sandblasted coupons, and some were epoxied to coupons that were sandblasted and polished. Some Tesa, Rebo, and Zebra labels were affixed to sandblasted coupons, and some were affixed to coupons that had been sandblasted and polished.

The ORNL team then scanned the barcode samples using a Webscan TruCheck DPM Tower like the one shown in Figure **2**. Barcode verifiers grade 2D barcodes printed on label material using ISO 15415 and grade 2D barcodes directly marked on metal using ISO 29158 (AIM-DPM).

Figure 2: Webscan TruCheck DPM Tower

3. Accelerated Environmental Tests

ORNL leased an environmental enclosure from Thermal Product Solutions to perform the temperature testing at ORNL and contracted with Q-lab and Global Testing Laboratories as third-party testing laboratories to perform 9 other tests. Q-Lab performed the following tests at their facilities: xenon arc lamp, UVA, UVB, combined UVA with salt fog. Global Testing Laboratories performed the cyclic corrosion and impact testing at their facilities and are scheduled to finish the corrosion, blowing sand/dust, and high pressure and temperature water jet testing at their facility. Each of these tests are further described in the following sections.

3.1. Q-SUN xenon arc lamp testing

Q-Labs staff installed 22 samples into a Q-SUN Xe-3 xenon arc lamp tester as shown in Figure 3. Testing followed a cycle like ASTM G155 Cycle 1. Samples were exposed for 102 min of light at 63°C black panel temperature, then 18 min of light and water spray. These cycles were repeated for a total 500 h. An irradiance of 0.55 W/m2 at 340 nm was used [4].

Figure 3: ORNL samples installed in Q-SUN Xe-3 Xenon arc test chamber.

3.2. QUV UVA testing

Q-Labs staff installed 24 samples into a QUV tester with UVA bulbs as shown in Figure 4 and Figure 5. Testing followed a cycle like ASTM G154 Cycle 1. Samples were exposed for 8 h of light at 60°C black panel temperature followed by 4 h of condensation at 50°C black panel temperature. These cycles were repeated for a total of 500 h. Fluorescent UVA-340 bulbs at 340 nm were used with an irradiance of 0.89 W/(m^2 • nm) [5].

Figure 4: ORNL samples installed in QUV chamber. Samples are shown facing out but were turned inward toward UV lamps for testing.

Figure 5: ORNL samples installed in QUV test chamber for UVA testing.

3.3. QUV UVB testing

Q-Labs staff installed 24 samples into a QUV tester with UVB bulbs similar to the setup shown in Figure 4 and Figure 5. Testing followed a cycle like ASTM G154 Cycle 2. Samples were exposed for 4 h of light at 60°C black panel temperature followed by 4 h of condensation at 50°C black panel temperature. These cycles were repeated for a total of 500 h. Fluorescent UVB-313 bulbs at 310 nm were used with an irradiance of 0.71 W/(m^2 • nm) [5].

3.4. QUV and Q-Fog testing

Testing followed ASTM D5894. Q-Labs staff exposed 24 samples to alternating weeks of one week in a fluorescent UV chamber followed by one week in a salt fog chamber. In the UV chamber, samples were set up similarly to what is shown in shown in Figure 4 and Figure 5. The samples were exposed for 4 h of light at 60°C black panel temperature followed by 4 h of condensation at 50°C black panel temperature. Fluorescent UVA-340 bulbs at 340 nm were used with an irradiance of 0.89 W/(m^2 • nm). In the salt fog chamber, samples were set up as shown in Figure 6 and exposed to 1 h of fog at ambient temperature then a 1 h dry off at 35°C. The fog solution was 0.05% sodium chloride and 0.35% ammonium sulfate [6].

Figure 6: ORNL samples installed in Q-Fog test chamber.

3.5. Temperature testing

ORNL staff leased a Tenney TC20RC environmental enclosure from Thermal Product Solutions and had it installed at ORNL. ORNL staff then installed 61 samples as shown in Figure 7. All samples that were affixed to the ½ in. thick steel coupons were hung vertically. A few stainless samples that were not affixed to such coupons were laid flat on the stainless wire racks with their markings facing up. Samples were exposed to -40°C for 7 days then 113°C for 7 days. These cycles were repeated for a total of 6 weeks. Relative humidity was not controlled. The temperature ramp rate was not controlled such that the temperature changed as quickly as the chamber's heating and cooling capacity permitted.

Figure 7: ORNL samples in Tenney TC20RC environmental enclosure.

3.6. Cyclic corrosion testing

Staff at Global Testing Laboratories installed 63 samples into a salt fog chamber as shown in Figure 8. Samples were exposed to five cycles that consisted of the following steps:
1. Ambient stage with stress: salt fog at ambient temperature for 8 h
2. Humid stage: 49–60°C at approximately 95% relative humidity for 8 h
3. Dry stage: 60°C at less than 30% relative humidity for 8 h

This testing is similar to that described by GM Cyclic Corrosion Laboratory Test (GMW 14872).[7]

Figure 8: ORNL samples installed in salt fog chamber

3.7. Corrosion testing

Staff at Global Testing Laboratories are scheduled to test 57 samples in a salt fog chamber. The samples will be arranged similarly to those shown in Figure 8. The testing is planned to follow ASTM B117, “Standard Practice for Operating Salt Spray (Fog) Apparatus.”[8]

3.8. Blowing sand/dust testing

Staff at Global Testing Laboratories are scheduled to test 57 samples in a blowing sand/dust chamber. The testing is planned to follow MIL-STD 810G 510.6, “Sand and Dust 4.1 Procedure I – Blowing Dust,” except temperature and humidity will not be controlled.[9]

3.9. Impact testing

Staff at Global Testing Laboratories completed impact testing of 55 samples. Testing followed IEC 61010-1, Section 8.2.2, “Impact Test.” A smooth steel sphere with a mass of 500 g was allowed to fall freely from a distance of 1000 mm onto each of the samples as shown in Figure 9. [10]

Figure 9: Impact testing allowed a 500 g smooth steel sphere to fall from 1000 mm onto each of the samples.

3.10. High pressure and temperature water jet

Staff at Global Testing Laboratories are scheduled to subject 57 samples to high-pressure and -temperature water jets. Testing is planned to follow IEC 60529 CORR 1 IEC 60529 CORR 1 - Degrees of Protection Provided by Enclosures (IP Code) - Edition 2.2, Test 14.2.9 “Test for second characteristic numeral 9 with a spray nozzle”[11]

4. Qualitative Results

ORNL has received samples back from tests 1 through 5. Tests 7 and 9 have also been completed, but the samples have not yet been returned. The remaining tests are expected to be completed during the summer of 2019.

Many of the samples including stainless steel samples that were not affixed to A516 steel and nonmetallic labels appear rusty. While we expected the untreated surface of the A516 steel to rust, we were surprised how the rust spread over stainless and nonmetallic labels. This behavior was exceptionally apparent for the samples that underwent cyclic corrosion testing (test 6) and QUV & Q-Fog testing (test 4) but also to a lesser degree in the samples that were subjected to the UVA and UVB testing.

We observed that the Rebo labels subjected to temperature testing discolored. As shown in the side-by-side images in Figure 10 below, the Rebo labels discolored dramatically. We suspect the high temperatures caused the discoloration. We did not observe discoloring amongst the other nonmetallic labels nor with the other tests.

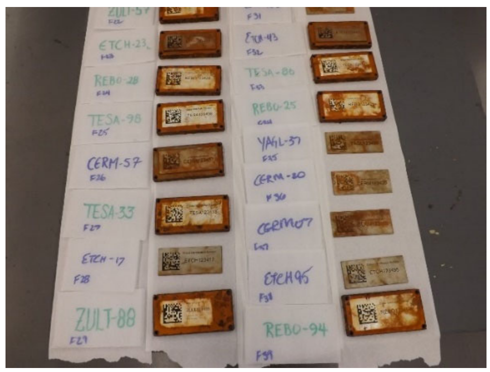

Figure 10: Image of selected samples after cyclic corrosion testing.

5. Selected Quantitative Results

As mentioned earlier, all samples were scanned before and after accelerated environmental testing. ORNL is still analyzing the data and plans a more comprehensive quantitative report later in 2019. ORNL configured the barcode verifier to produce a PDF report as well as a CSV summary file for each scan. The PDF report includes summary information at the top that provides the data, symbology, and grades for any tests selected. As shown in Figure 11, ORNL recorded results for both ISO 15415 and ISO 29158 for each sample; however, the ISO 15415 results are only meaningful for the label barcodes, and the ISO 29158 results are only meaningful for the DPMs. Figure 12 shows the ISO 29158 results for a laser-etched stainless steel sample that was part of test 4 (QUV and Q-Fog testing). As shown in Figure 11 and Figure 12, this sample received a C grade after environmental exposure. This same sample received an A grade before environmental exposure.

Webscan TruCheck™ USB Verification Report

Software Version: 3.03.54, Unit Serial: TC-825-0318-121
Verified: Tue 16-Apr-2019 03:01:04 PM, Last Calibrated: Tue 16-Apr-2019 11:59:30 AM

Page 1 of 2

Report Summary	
Data	YAGL123412
Symbology	DataMatrix
Verified By	ORNL_Admin

Verification Grades

Standard	Grade	Aperture	Wavelength	Lighting	Formal Grade	Notes
ISO15415	F (0.0)	20	660	45	0.0/20/660/45	
ISO29158 (AIM-DPM)	C (2.0)	81	660	45Q	DPM 2.0/81/660/45Q	[Warning]Symbol X-Dimension out of range

Figure 11: Top portion of Webscan Verification Report

Webscan TruCheck™ USB Verification Report

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Page 2 of 2

Image

General Characteristics	
Matrix Size	14x14 (Data: 12x12)
Horizontal BWG	10%
Vertical BWG	-33%
Encoded characters	10
Total Codewords	18
Data Codewords	8
Error Correction Budget	10
Errors Corrected	0
Error Capacity Used	0
Error Correction Type	ECC 200
Image	Black on white
Nominal X Dim	100.5 mil
Contrast Uniformity	49 at module(5,1)
Stability	98%

Data Matrix Codewords

5A 42 48 4D 8E A4 8E 81 2B B1 42 11 42 68 44 07 D3 9A

*=Fixed by Error Correction

Modulation Values

41	50	73	60	83	56	75	77	86	84	84	99	99	99	99	99
50	99	71	99	71	99	81	92	77	94	90	86	99	46	99	99
58	99	64	99	79	81	83	92	86	95	94	71	99	99	29	99
64	99	62	73	77	88	90	92	90	85	96	99	99	99	99	99
50	99	56	99	77	83	81	97	99	96	98	76	99	99	44	99
43	99	99	99	71	99	97	96	98	91	99	99	83	79	99	99
47	99	49	99	62	81	90	86	99	99	94	89	99	76	61	99
39	99	60	99	73	77	84	96	99	99	83	99	99	99	99	99
37	99	60	99	99	81	84	79	99	99	99	99	99	68	46	99
69	99	99	88	99	98	81	88	94	73	99	99	99	71	99	99
75	99	86	94	83	79	99	92	94	99	73	99	99	67	41	99
94	99	99	92	99	99	99	99	99	89	99	77	70	61	99	99
90	99	96	99	99	99	99	99	99	95	99	83	99	99	38	99
92	99	99	98	99	99	99	99	99	99	99	99	85	70	99	99
69	99	99	99	99	99	99	99	99	99	99	89	79	73	64	99
66	83	86	94	99	99	99	99	99	99	99	99	99	99	99	99

ISO 29158 Quality Parameters

1. Unused Error Correction (UEC)	100%	A		PASS
2. Cell Contrast (CC)	58%	A	Rl/Rd (100/42)	PASS
3a. Cell Modulation (CMOD)		A		PASS
3b. Reflectance Margin (RM)		A		PASS
4. Axial Nonuniformity (ANU)	2%	A		PASS
5. Grid Nonuniformity (GNU)	15%	A		PASS
6. Fixed Pattern Damage (FPD)	2.0	C		PASS
7. Left 'L' Side (LLS)		A		PASS
8. Bottom 'L' Side (BLS)		A		PASS
9. Left Quiet Zone (LQZ)		C		PASS
10. Bottom Quiet Zone (BQZ)		A		PASS
11. Top Quiet Zone (TQZ)		A		PASS
12. Right Quiet Zone (RQZ)		A		PASS
13. Top Transition Ratio (TTR)	0%	A		PASS
14. Right Transition Ratio (RTR)	0%	A		PASS
15. Top Clock Track (TCT)		A		PASS
16. Right Clock Track (RCT)		B		PASS
17. Distributed Damage Grade (DDG)	4.0	A		PASS
18. DECODE		A		PASS
19. Minimum Reflectance (MR)	41%	A		PASS

Figure 12: Bottom portion of Webscan verification report showing ISO 29158 quality parameters related to DPMs.

Table 1 shows the before and after values for each of the metrics used as part of the ISO 29158 grading. We've highlighted several key metrics that changed dramatically between the before and after verification scans. Cell contrast refers to the relative contrast between the light and dark modules. Cell contrast is calculated as the difference between the mean of the light and dark areas divided by the mean of the light area. Cell contrast values greater than 30% will be graded as an A. Rl/Rd is a ratio of the reflectance of the light modules to the reflectance of the dark modules. This parameter is not directly used for ISO 29158 grading. Fixed pattern damage is an overall grade for all the fixed pattern components and is equal to the lowest-grade fixed pattern components (left "L" side, bottom "L" side, left quiet zone, bottom quiet zone, top quiet zone, right quiet zone, top transition ratio, right transition ratio, top clock track, and right clock track). In this example, after environmental testing the right clock track grade fell from an A to a B, and the left quiet zone fell from an A to a C grade. The new left quiet zone grade was the lowest and caused the fixed pattern damage to fall from an A to a C.

ISO 29158 Quality Parameters	Before Testing				After Test 4 (QUV & Q-Fog)			
1. Unused Error Correction (UEC)	100%	A		PASS	100%	A		PASS
2. Cell Contrast (CC)	70%	A	Rl/Rd (100/30)	PASS	58%	A	Rl/Rd (100/42)	PASS
3a. Cell Modulation (CMOD)		A		PASS		A		PASS
3b. Reflectance Margin (RM)		A		PASS		A		PASS
4. Axial Nonuniformity (ANU)	1%	A		PASS	2%	A		PASS
5. Grid Nonuniformity (GNU)	3%	A		PASS	15%	A		PASS
6. Fixed Pattern Damage (FPD)	4.0	A		PASS	2.0	C		PASS
7. Left "L" Side (LLS)		A		PASS		A		PASS
8. Bottom "L" Side (BLS)		A		PASS		A		PASS
9. Left Quiet Zone (LQZ)		A		PASS		C		PASS
10. Bottom Quiet Zone (BQZ)		A		PASS		A		PASS
11. Top Quiet Zone (TQZ)		A		PASS		A		PASS
12. Right Quiet Zone (RQZ)		A		PASS		A		PASS
13. Top Transition Ratio (TTR)	0%	A		PASS	0%	A		PASS
14. Right Transition Ratio (RTR)	0%	A		PASS	0%	A		PASS
15. Top Clock Track (TCT)		A		PASS		A		PASS
16. Right Clock Track (RCT)		A		PASS		B		PASS
17. Distributed Damage Grade (DDG)	4.0	A		PASS	4.0	A		PASS
18. DECODE		A		PASS		A		PASS
19. Minimum Reflectance (MR)	37%	A		PASS	41%	A		PASS

Table 1: ISO 29158 metrics recorded before and after QUV and Q-Fog testing of YAGL123412.

6. Key Observations Conclusions, Lessons Learned and Next Steps

The analysis to date suggests that CerMark-coated laser-etched markings appears to be a good choice for global identifier markings. While anecdotal evidence suggests that chemically etched markings and epoxy adhesives may fail over time, the initial test data is inconclusive about these points. Preliminary qualitative assessments suggest that Zebra Ultimate, Zebra Endure, or Tesa labels can serve as a medium-term solutions to add a supplemental global identifier label to previously fabricated UF_6 cylinders in circulation before they are due for recertification. The limited quantitative data suggests laser-etched markings without CerMark should not be adopted for the global identifier.

The ORNL team was surprised to find the Rebo labels, but none of the other nonmetallic samples, subjected to temperature testing discolored. The barcode verifier also had trouble decoding several of the laser-etched (but not the CerMark-coated laser-etched) samples after environmental exposure.

The team was also surprised by the extensive rust on the nonmetallic and stainless portions of the samples. If similar testing is conducted in the future, it will be more representative to paint or otherwise treat the bare A516 portions of the samples before environmental exposure because bare A516 is typically not exposed after cylinder manufacture.

The ORNL team is working with Global Testing Laboratories to complete the remaining tests, at which point the ORNL team will prepare a more extensive quantitative analysis of the data.

7. Acknowledgments

Funding for this project was provided by the Department of Energy's NNSA Office of International Nuclear Safeguards (OINS). The authors would also like to thank Scott Palko for his assistance preparing samples for testing and Ed Wonder for his assistance refining the test plan.

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