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Evaluating Barcode Size and Metal Surface Treatment Options for a Global UF_6 Cylinder Identifier

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OAK RIDGE National Laboratory

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ACRONYMS

COTS	commercial off-the-shelf
DPM	direct part marking
ORNL	Oak Ridge National Laboratory
UF_6	uranium hexafluoride
WNTI	World Nuclear Transport Institute

EXECUTIVE SUMMARY

A team at Oak Ridge National Laboratory tested various barcode sizes, materials, surface finishes, and marking techniques to determine suitable direct part marking techniques and barcode specifications for a new uranium hexafluoride (UF_6) cylinder global identifier. This paper describes testing those variables at different read distances and angles with several commercial off-the-shelf direct part mark or barcode readers. This research concluded that a 1.4 in. 2D Data Matrix barcode with a 0.1 in. quiet zone would be appropriate for the machine-readable feature on the proposed UF_6 cylinder global identifier. Testing suggests that this size barcode could be read from an angle of up to 30° over the range of 10–100 cm using multiple commercial off-the-shelf handheld direct part mark or barcode readers. Testing also suggested that barcodes marked on ball-blasted stainless steel with CerMark laser marking ink may be a good choice for the proposed UF_6 cylinder global identifier because they exhibited high contrast and were readable from a desirable range of distances and angles.

1. INTRODUCTION

In May 2014, the World Nuclear Transport Institute (WNTI) formed a special working group to evaluate and develop new standards for identifying uranium hexafluoride (UF_6) cylinders. Over the last few years this working group worked to better understand how a global UF_6 cylinder identifier with machine-readable features would impact the industry.

Several technologies were considered for the machine-readable feature of the cylinder identifier, and barcodes emerged as the most practical feature. Although 1D barcodes are common and can include error checking, 2D barcodes typically include error checking and error correction features that are not commonly available with 1D barcodes.

There are several 2D barcode formats. One of the most widely used for industrial purposes is the Data Matrix barcode defined in ISO/IEC 16022:2006(E). Data Matrix barcodes are usually square and consist of cells or modules that can be light or dark. These modules form an outer border with an L-shaped "finder pattern" and alternating "timing pattern" on the opposite sides. Inside the border, only some modules are required to encode data. Other modules are used for padding and error correction, and some are unused. The barcode must also be surrounded by quiet space, which is negative or white space acting as a buffer from other markings. Figure 1 (*left*) shows a Data Matrix barcode encoding "Wikipedia" and (*right*) shows the same barcode highlighted to indicate the function of each module.

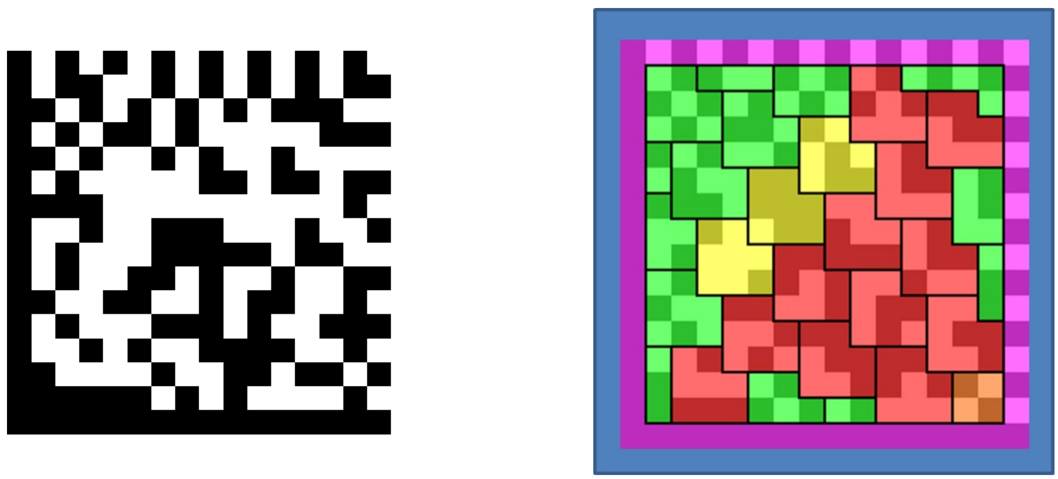


Figure 1. Example Data Matrix barcode encoding "Wikipedia." (*Left*) Data matrix barcode. (*Right*) Data matrix barcode highlighted to show the function of each module: data (*green*), padding (*yellow*), error correction (*red*), synchronization (*magenta*), unused (*orange*), and quiet zone (*blue*).[1]

To support the WNTI working group, Oak Ridge National Laboratory (ORNL) investigated direct part marking (DPM) techniques and barcode specifications that would be applicable for the global UF_6 cylinder identifier. That testing evaluated how several commercial off-the-shelf (COTS) DPM or 2D barcode readers performed when varying the size of the barcode, read distance, read angle, material, surface finish, and marking technique. For example, one set of tests evaluated the read range of several DPM or 2D barcode readers to read a 5 cm 2D Data Matrix barcode printed on cardstock.

[1] Adapted from J. Laventhol. 2013. Datamatrix-modulecolours.png. https://en.wikipedia.org/wiki/Data_Matrix#/media/File:Datamatrix-modulecolours.png. Used under CC0 1.0 license.

2. TESTING THE SUITABILITY OF DIRECT PART MARKING TECHNIQUES AND BARCODE SPECIFICATIONS

2.1 NOMINAL USE CASE

To assess what barcode sizes and surface finishes would work well for the global identifier, the ORNL researchers needed to better understand how users would use the machine-readable features of the global UF_6 cylinder identifier. To elicit feedback, the ORNL team proposed a nominal use case to the WNTI working group. The ORNL researchers proposed that most users would like to be able to read the barcode using a handheld barcode reader starting from about 10 cm away and up to 100 cm away from the barcode surface. Additionally, the ORNL team proposed that users would like to be able to read the barcode at an angle of up to 30°. The ORNL researchers proposed this use case to the WNTI working group, which accepted the use case without modification.

2.2 REPRESENTATIVE SET OF DPM OR BARCODE READERS AND TEST APPARATUS

Eight COTS DPM or 2D barcode readers (referred to as *readers* throughout this report) were selected. The selected readers were chosen based on vendor recommendations for their ability to read markings directly applied to metals. The selected readers are shown in Table 1 are from several manufacturers and range in cost from $700 to $2,700.

Table 1. Barcode readers used for testing

#	1	2	3	4
Brand	Keyence	Cognex	Intermec	Intermec
Model	HR-100	DataMan 8600	SR61TDPM	SR61TXR
Cost	$770	$2,645	$857	$857
Picture				

Table 1 (continued). Barcode readers used for testing

#	5	6	7	8
Brand	Microscan	Microscan	Datalogic	Symbol/Zebra
Model	HS-41X Handheld DPM Reader	Mobile Hawk	PowerScan PD9530-DPM Evo	DS3508-DP
Cost	$826	$1,878	$797	$1,001
Picture				

The apparatus shown in Figure 2 was constructed to support the testing activities. It includes a sliding arm (shown on the left of the left image) to adjust the distance between the barcode reader and the barcode sample. During testing, the tester oriented the front of the barcode reader on the top leading edge of the sliding arm. The sample holder (shown in detail on the right image) can be rotated about the y-axis (vertical axis) to control the angular orientation of the barcode.

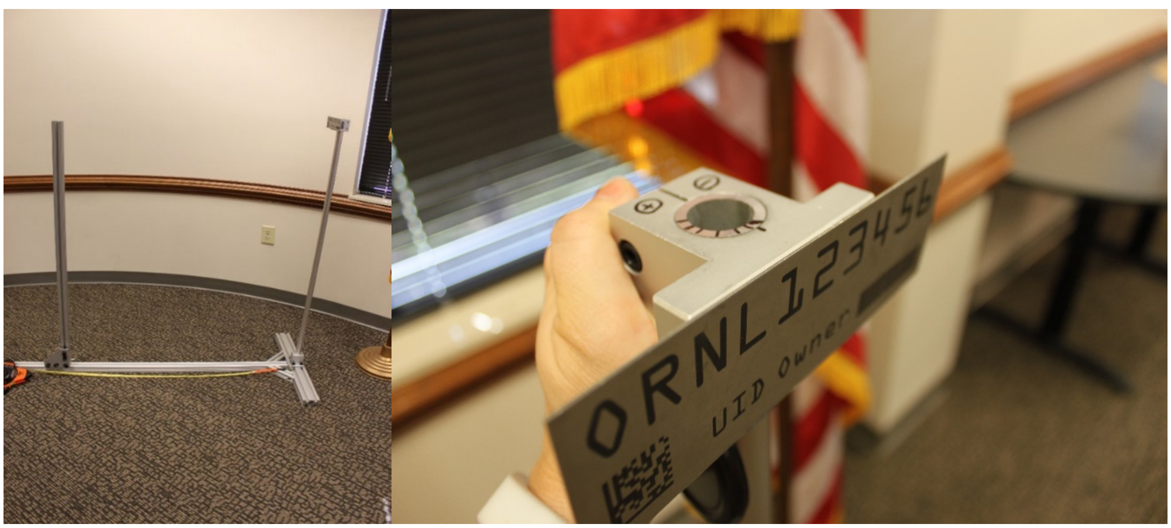


Figure 2. Test apparatus. (Left) View of complete apparatus (Right) Close up of rotating head

2.3 PHASE 1—TESTING 2.5 CM, 5 CM, AND 10 CM DATA MATRIX BARCODES

The authors printed a 2.5 cm, 5 cm, and 10 cm Data Matrix barcode on sheets of white cardstock using a laser printer. These barcode as shown in **Error! Reference source not found.** were used for testing throughout the following report subsections.

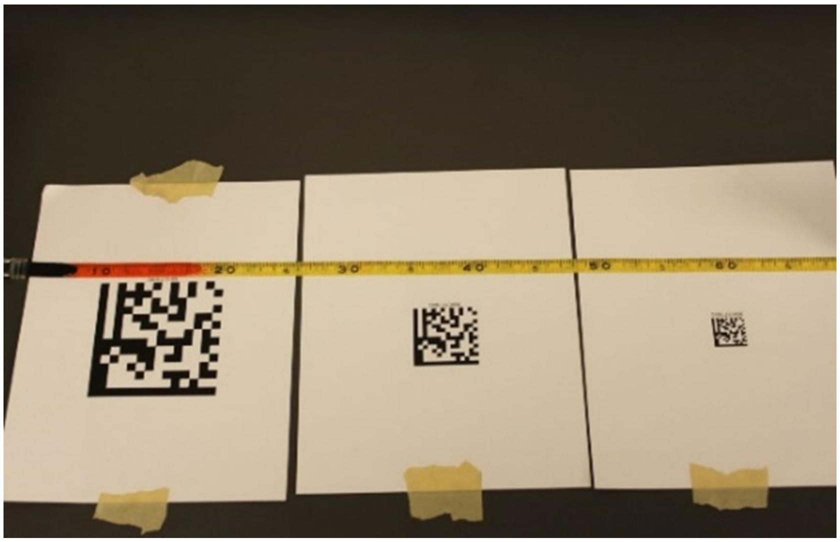


Figure 3. ***From left to right,*** **a 10 cm, 5 cm, and 2.5 cm Data Matrix barcode printed on 8.5 × 11 in. cardstock shown with a metric tape measure for perspective.**

2.3.1 Predetermined Distance Testing

To better understand how the size of the barcode affects a reader's readable range, the performance of the selected readers was evaluated at different distances from the barcode sample, and these tests were repeated for three different sizes of 2D Data Matrix barcodes. Each barcode size was evaluated at 14 predetermined distances ranging from contact to 20 m (0 cm, 5 cm, 10 cm, 15 cm, 20 cm, 30 cm, 60 cm, 1 m, 2 m, 3 m, 5 m, 10 m, 15 m, and 20 m), with each reader positioned normal, or "straight-on," to the barcode surface. Each barcode reader was tested at each distance. Figure 4, Figure 5, and Figure 6 show the results of testing each reader at each distance for each barcode size.

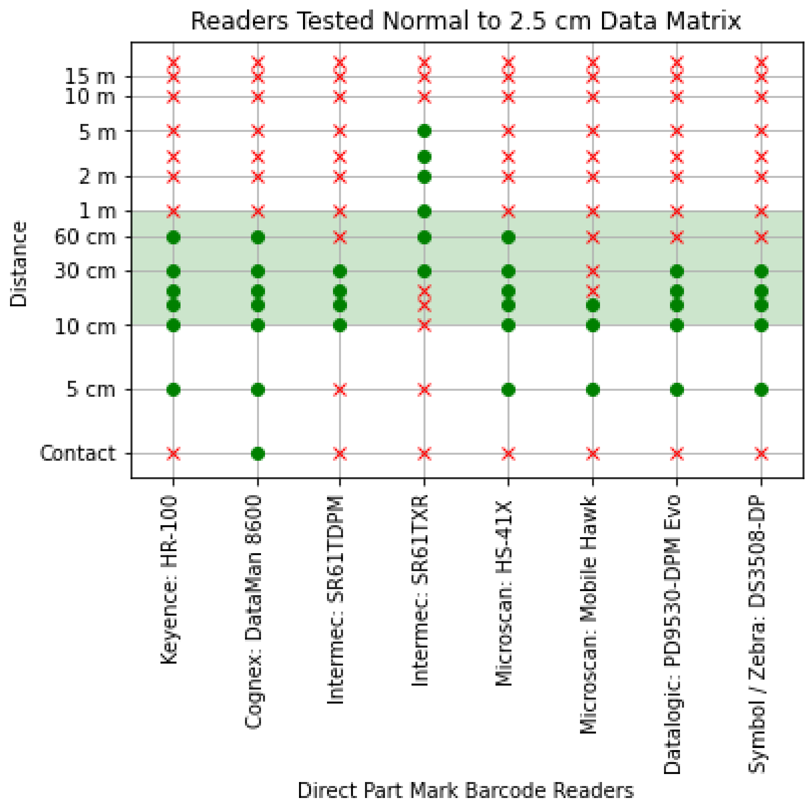


Figure 4. Reader performance at different distances for a 2.5 cm Data Matrix barcode printed on cardstock. The use case range is highlighted in green. Green dots represent successful reads, and red *x*'s represent unsuccessful reads.

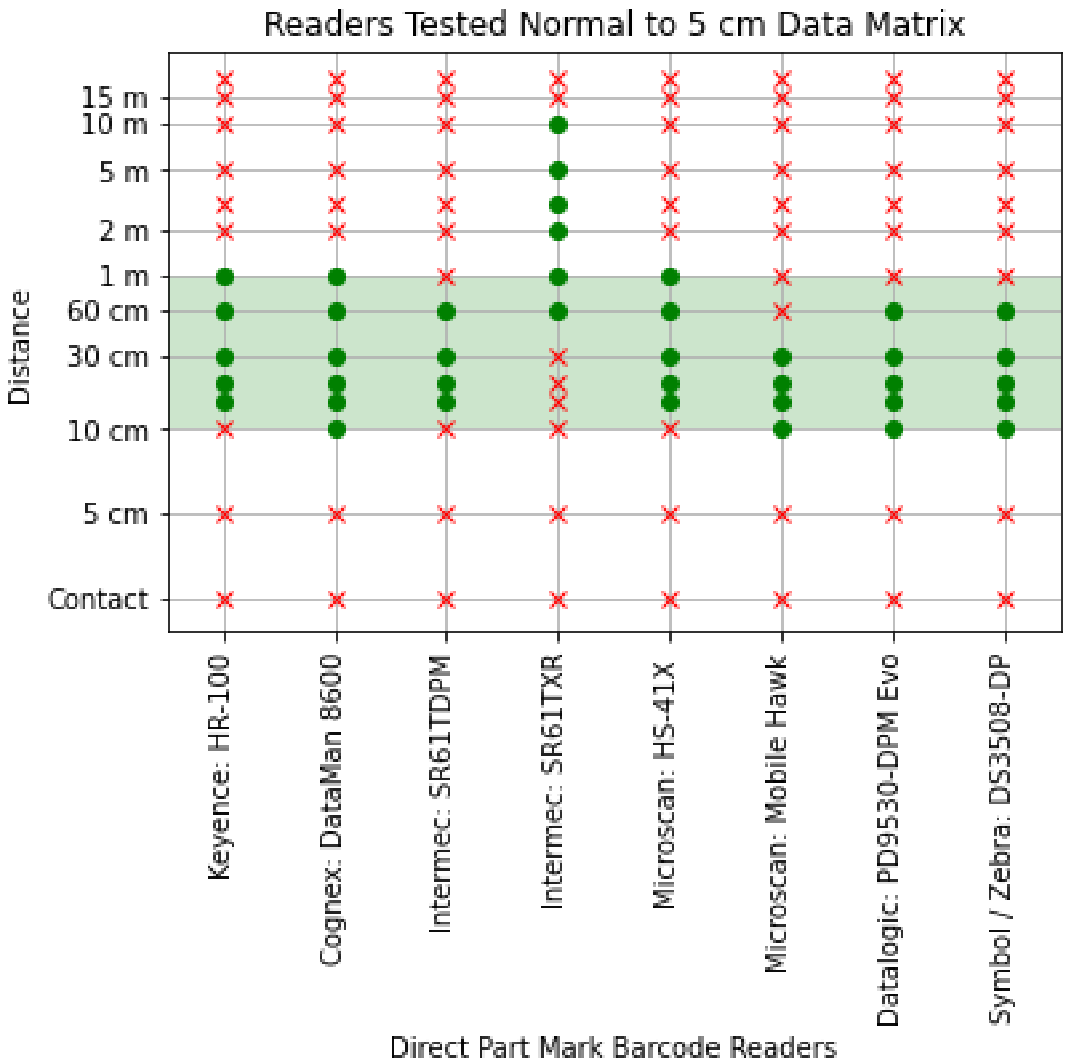


Figure 5. Reader performance at different distances for a 5 cm Data Matrix barcode printed on cardstock. The use case range is highlighted in green. Green dots represent successful reads, and red *x*'s represent unsuccessful reads.

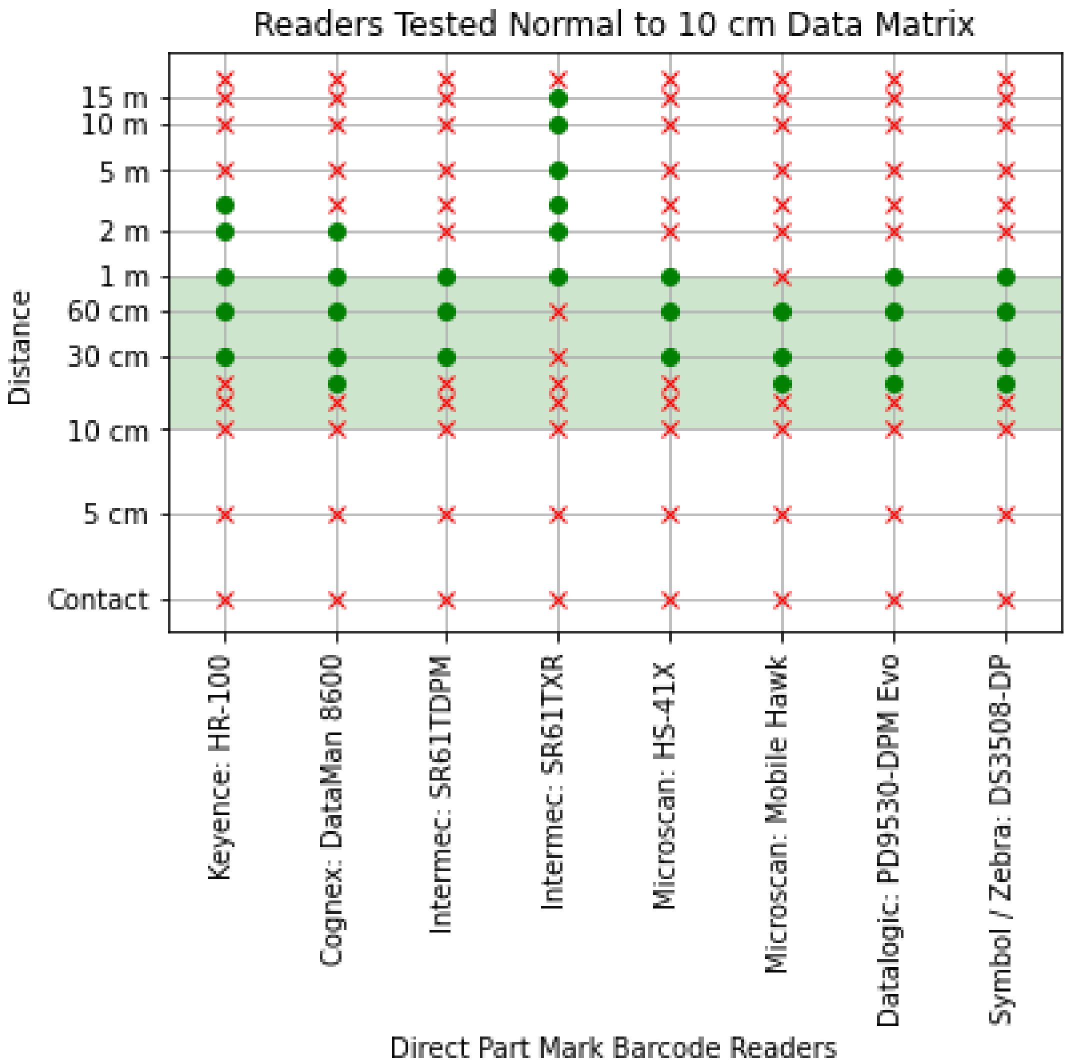


Figure 6. Reader performance at different distances for a 10 cm Data Matrix barcode printed on cardstock. The use case range is highlighted in green. Green dots represent successful reads, and red *x*'s represent unsuccessful reads.

The results show that as the size of the barcode increased, the reading range for each reader (the minimum read distance to maximum read distance) shifted to longer distances. The *effective read range* for each barcode size is the range that at least three of the eight readers were able to successfully read the barcode. Using this definition, the effective read range is 5 cm to 60 cm for the 2.5 cm barcode, 10 cm to 100 cm for the 5 cm barcode, and 20 cm to 200 cm for the 10 cm barcode. These results are summarized in Table 2.

Table 2. Effective read range for each Data Matrix barcode size printed on cardstock.

Data Matrix Barcode size	Effective read range Minimum (cm)	Maximum (cm)
2.5	5	60
5	10	100
10	20	200

2.3.2 Adaptive Range Determination Testing

The test described in the previous section was envisioned before testing began and did not provide sufficient precision when defining the minimum and maximum read distances. For this second set of tests, each barcode reader was placed in contact with the barcode face. The tester attempted to read the barcodes continuously as they moved the reader away from the face of the barcode, noting the first and last points the reader successfully read the barcode. Near the minimum and maximum distances, the tester could move the reader back and forth adaptively based on whether the reader was decoding the barcode to more precisely define the range compared to the predetermined distance test. Figure 7 shows the range for each reader at each barcode size determined using this adaptive approach.

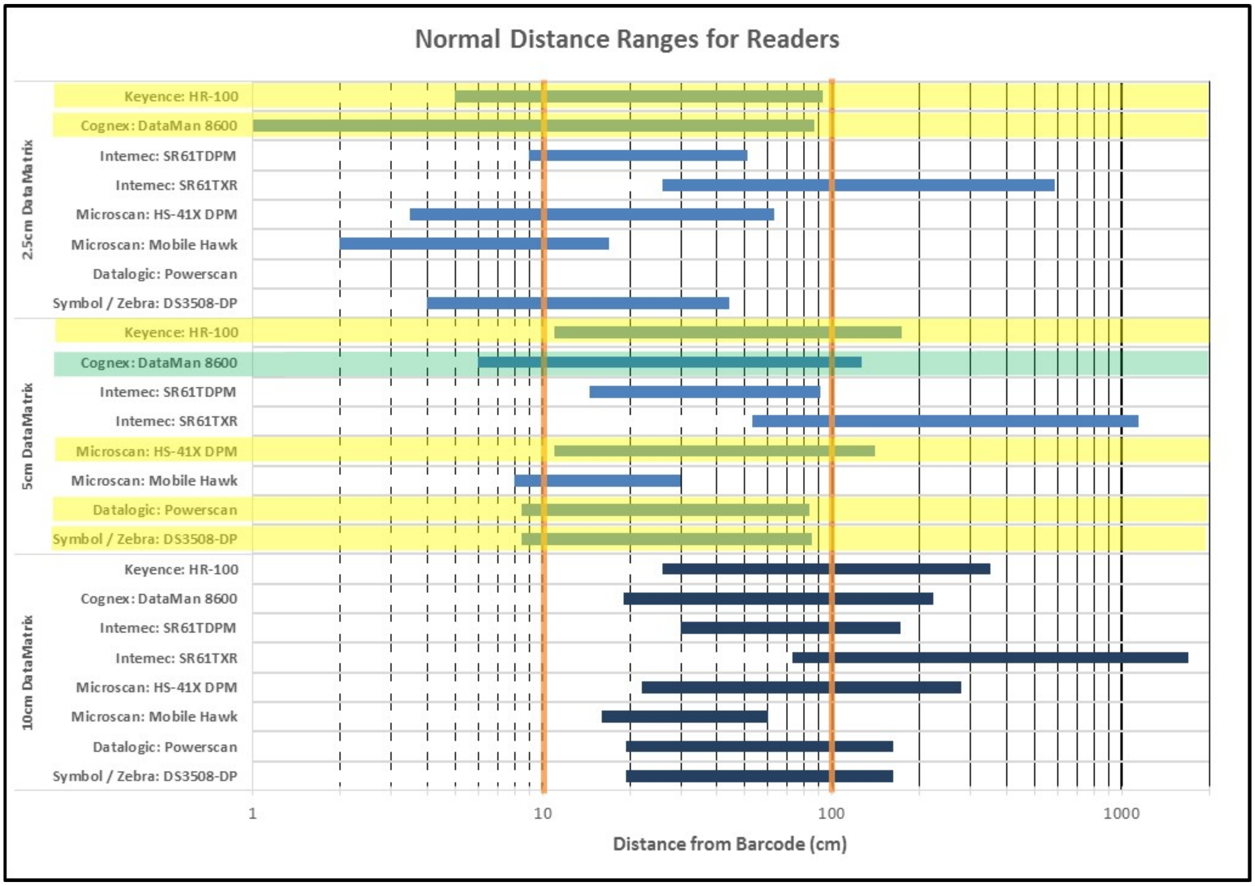


Figure 7. Normal Read range for each reader for 2.5 cm, 5 cm, and 10 cm Data Matrix barcodes printed on cardstock. The use case range is bounded by the orange vertical lines. Rows highlighted in yellow indicate readers that read the barcodes over most of the use case range, and rows highlighted in green indicate readers that read the barcodes over the entire use case range.

This testing suggests the effective read range[2] is 3–85 cm for the 2.5 cm barcode, 9–129 cm for the 5 cm barcode, and 20–256 cm for the 10 cm barcode. As shown in Table 3, this adaptive range testing provides additional precision to the effective read range of each barcode size and corroborates the results from the predetermined distance testing described in Section 2.3.1 and summarized in Table 2.

[2] The effective read range for each barcode size is the range that at least three of the eight barcode readers were able to successfully read the barcode.

Table 3. Effective read range for each Data Matrix barcode size printed on cardstock for predetermined distance and adaptive range testing.

Data Matrix barcode size (cm)	Predetermined distance testing		Adaptive range testing	
	Min. read range (cm)	Max. read range (cm)	Min. read range (cm)	Max. read range (cm)
2.5	5	60	3	85
5	10	100	9	129
10	20	200	20	256

Based on these results, only one COTS barcode reader (Cognex DataMan 8600, highlighted in green in Figure 7) could read the 5 cm Data Matrix barcode over the entire desired range from 10 cm to 100 cm. None of the readers could read the 2.5 cm or 10 cm barcode over the entire range of the suggested nominal use case.

As highlighted in yellow in Figure 7, several readers nearly read the 2.5 cm and 5 cm barcode over the entire range. For the 2.5 cm barcode, the Keyence HR-100 read from 5 cm to 92.5 cm and the Cognex DataMan 8600 read from contact to 85.5 cm. These results fall just short of the upper limit of the use case range (100 cm). For the 5 cm barcode, the Keyence HR-100 read from 11 cm to 173 cm, and the Microscan HS-41X DPM read from 11 cm to 140 cm. These results fall slightly above the lower limit of the use case range (10 cm). A barcode sized between 2.5 cm and 5 cm, such as a 3.5 cm barcode, may allow the Keyence HR-100 and Microscan HS-41X readers to successfully read the barcode over the entire suggested use case range.

2.4 PHASE 2—TESTING A 3.5 CM DATA MATRIX BARCODE

Additional barcode testing was conducted in late 2016 to better identify a barcode size which could be read by a larger number of readers over the entire suggested use case range. The researchers printed a 3.5 cm Data Matrix barcode on cardstock (Figure 8). Researchers conducted an adaptive range determination test as described in Section 2.3.2 using the 3.5 cm Data Matrix barcode. Results from the adaptive range determination are shown in Figure 9 along with the results from the 2.5 cm, 5 cm, and 10 cm barcodes. The readers that successfully covered the desired 10 cm to 100 cm use case range are highlighted in green. Readers that read the barcode over nearly the entire use case range are highlighted in yellow. Three readers including the Keyence HR-100, Cognex DataMan 8600, and Microscan HS-41X DPM were able to successfully read the 3.5 cm barcode over the nominal use case range.

Figure 8. 3.5 cm Data Matrix barcode on 8.5 × 11 in. cardstock shown with an inch and metric tape measure.

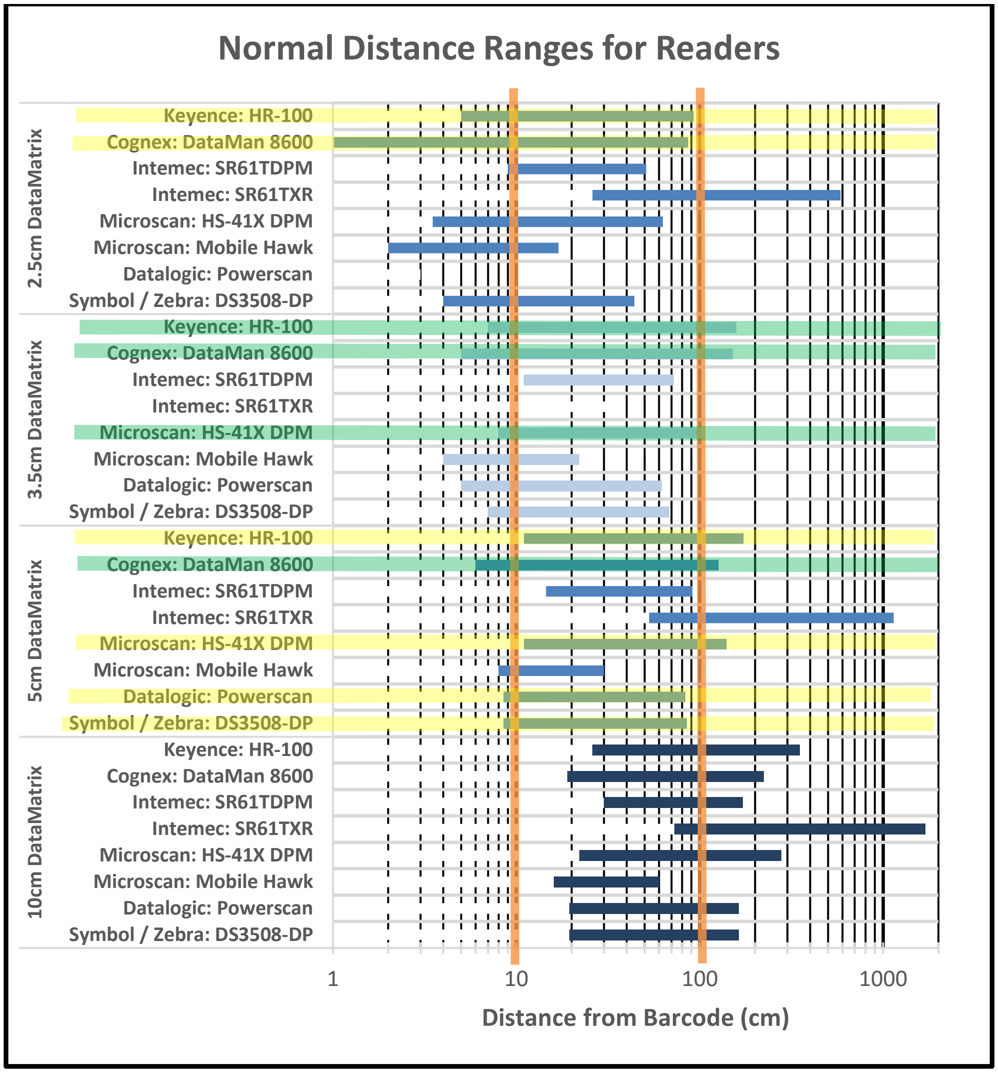


Figure 9. Read range for each reader for 2.5 cm, 3.5 cm, 5 cm, and 10 cm Data Matrix barcodes printed on cardstock. The use case range is bounded by the orange vertical lines. Rows highlighted in yellow indicate readers that read the barcodes over most of the use case range, and rows highlighted in green indicate readers that read the barcodes over the entire use case range.

2.5 PHASE 3—TESTING A 1.4 IN. DATA MATRIX BARCODE

Testing of the 3.5 cm barcode revealed that by varying the barcode size, the authors could identify a barcode size that multiple readers could read over the entire desired use case range. However, the authors realized in late 2016 and early 2017, that the ANSI specifications and suggested nameplate layout use imperial units. Although only a minor size difference exists between the 3.5 cm and 1.4 in. (3.56 cm) barcodes, a 1.4 in. barcode printed on cardstock was tested.

To better understand how distance and angle affect the effective read range for the 1.4 in. barcode, the readers were tested at different distances (5 cm, 10 cm, 15 cm, 20 cm, 30 cm, 40 cm, 50 cm, 60 cm, 70 cm, 80 cm, 90 cm, 100 cm, 110 cm, 120 cm, 130 cm, 140 cm, 150 cm, and 200 cm) and angles (0°, ±15°, ±30°,±45°, and ±60°) relative to the face of the barcode. Each distance and angle were tested using each barcode reader, regardless of any failures. Approximately 1,296 tests were conducted.

Testing results for each reader are shown in Figure 10. The test results indicate that the 1.4 in. barcode was readable by three readers over the entire 10–100 cm range for some angles, but only two readers (the Keyence HR-100 and Cognex DataMan 8600 readers) could read the barcode at up to 30° over the entire 10–100 cm range. For some angles, the Microscan HS-41X DPM could read the 1.4 in. barcode from 10 cm to 100 cm, but at 30° it could only read the barcode from 10 cm to 80 cm.

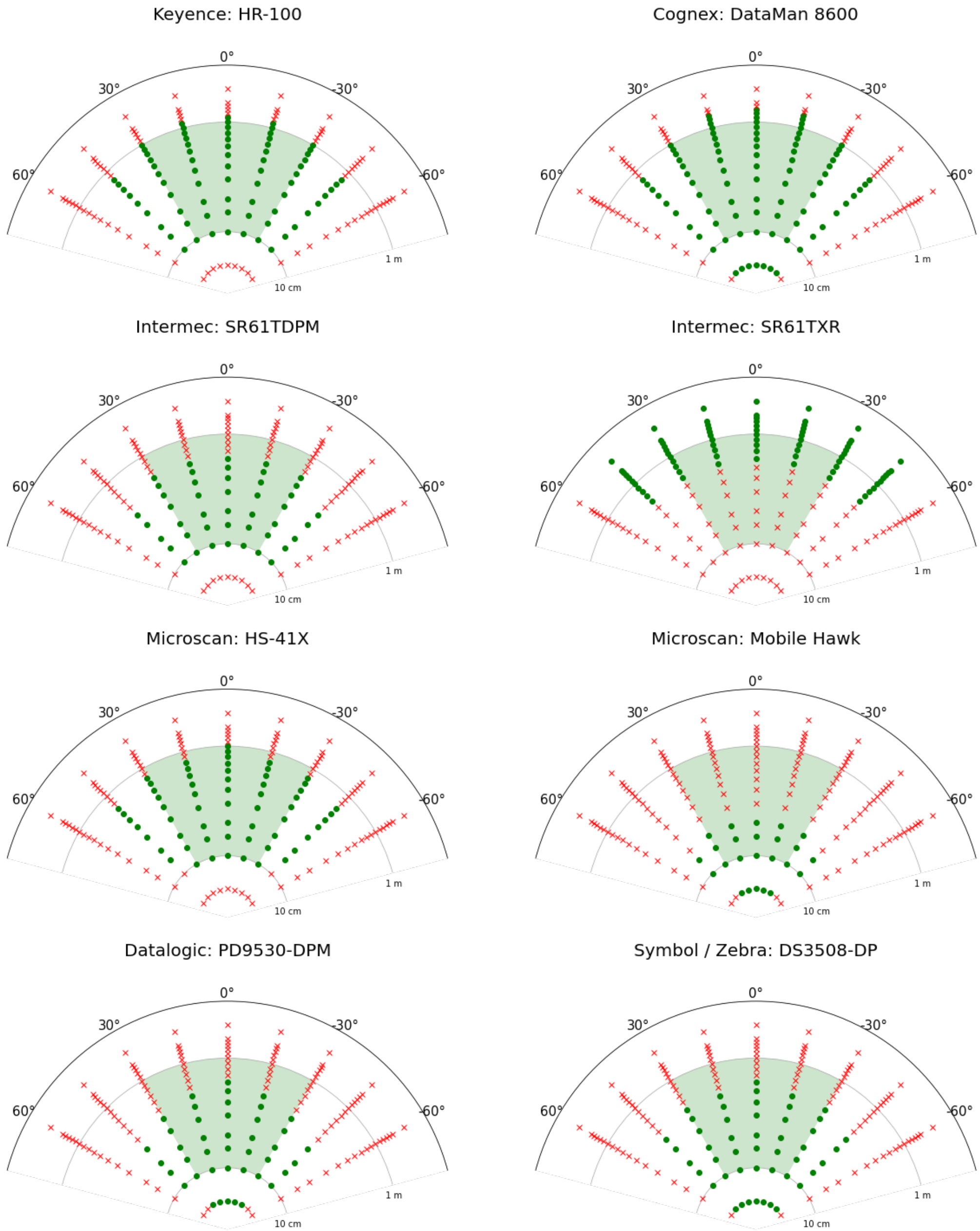
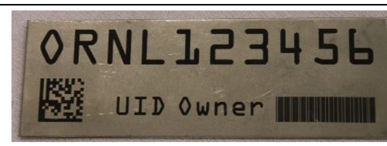
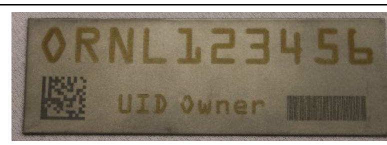


Figure 10. Reader performance at different distances and angles for a 1.4 in. Data Matrix printed on cardstock. The use case range is highlighted in green. Green dots represent successful reads, and red *x*'s represent unsuccessful reads.

2.6 TESTING PLATE MATERIALS, FINISHES, AND MARKING METHODS

A new global UF_6 cylinder identifier will need to be robust and capable of withstanding the environmental conditions cylinders are exposed to throughout their life cycle [4]. Stainless steel is often used for industrial applications with these requirements. Several marking methods are generally used to apply barcodes to metal parts, and dot peening and laser etching having the highest resistance to abrasion or wear. To better assess how different plate materials, finishes, and marking methods performed for the intended use case, the project acquired eight metal sample identifiers. The different combinations of materials, finishes, and marking techniques tested are summarized in Table 4. All samples contained a 2 cm Data Matrix barcode. A 2 cm barcode printed onto cardstock was also evaluated as a control.

Table 4. Summary of samples tested.

Short name	Surface finish	Metal	Marking technique	Image
Dot peen stainless	Mill	Stainless	Dot peening	
Black anodized aluminum	Black Anodized	Aluminum	Laser	
Aluminum	Mill	Aluminum	Laser	
Mirror finish stainless	Mirror	Stainless	Laser	
Ball-blasted stainless CerMark	Ball-blasted	Stainless	Laser with CerMark laser marking ink	
Ball-blasted stainless	Ball-blasted	Stainless	Laser	
Vertically brushed stainless	Vertical brush	Stainless	Laser	
Horizontally brushed stainless	Horizonal brush	Stainless	Laser	

2.6.1 Predetermined Distance Testing

Each plate was tested at six predetermined distances (5 cm, 10 cm, 15 cm, 30 cm, 1 m, and 2 m) similar to the testing described in Section 2.3.1. A comparison of the plates is shown in Figure 11. The mirror finish stainless sample and vertically brushed stainless sample performed very poorly. The dot peen marking method exhibited poor performance compared to the laser etched plates. The dot peen markings were also often difficult to visually inspect. The ball-blasted stainless with CerMark, ball-blasted stainless, and black anodized aluminum samples performed well compared to the cardstock.

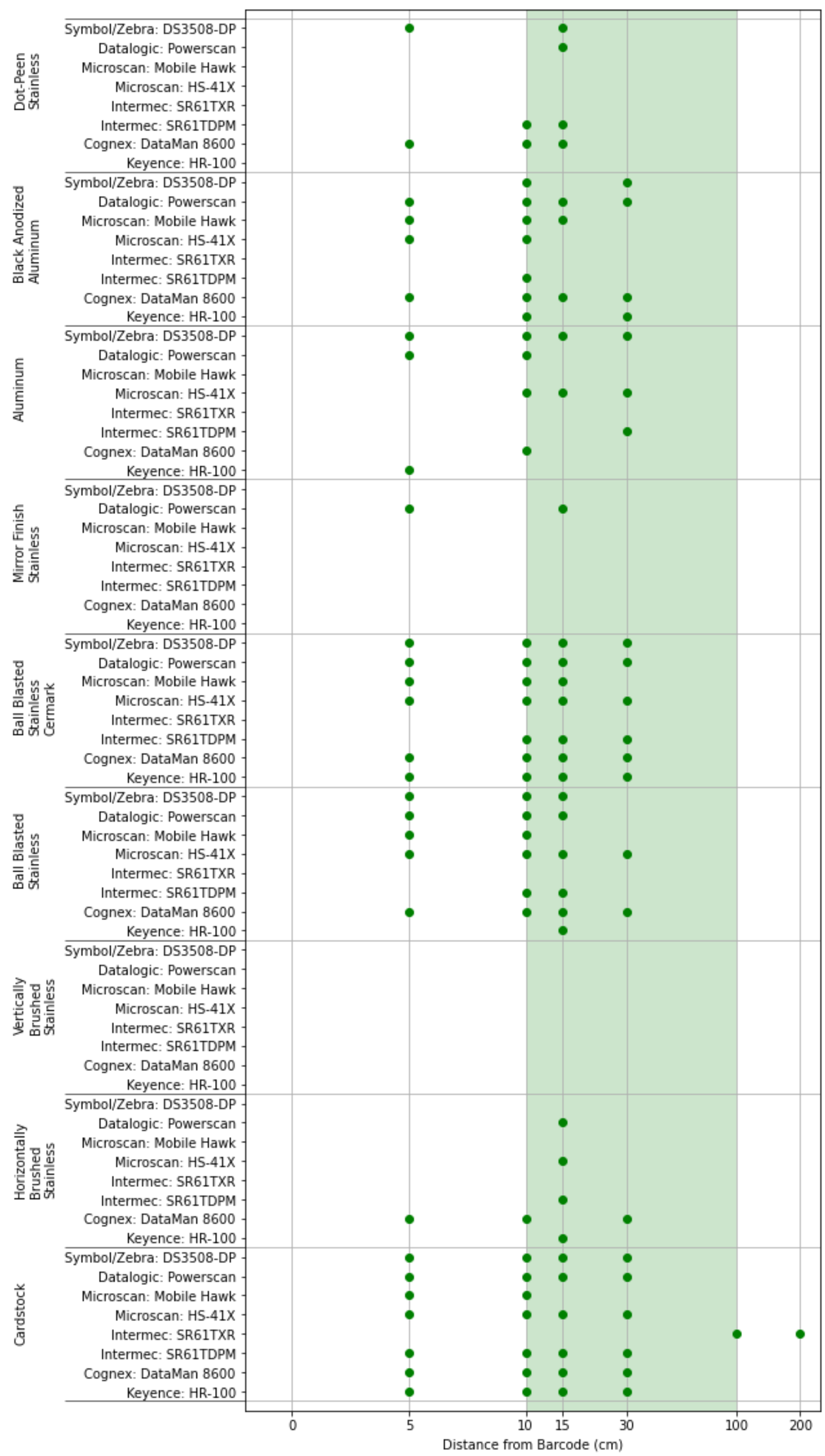


Figure 11. Comparison of material, finish, and surface marking technique. Green dots represent successful reads. Unsuccessful read attempts are not shown.

2.6.2 Characterizing Reading Performance at an Angle

To characterize how readable the previously described surface finishes and marking techniques are from various angles, the samples were tested using each of the readers at six distances (5 cm, 10 cm, 15 cm, 30 cm, 100 cm, and 200 cm), and seven angles (0°, ±30°, ±45°, ±60°). As with previous testing, each distance and angle were examined, regardless of previous failures. Approximately 336 tests were conducted per metal sample.

Table 5 illustrates the number of successful reads per material and the percentage of these reads out of the total number of tests for that material. The table shows both the readability just for the test positions in the use case as well as read attempts at angles and distances beyond those described in the use case. Out of the 96 tests per sample in the use case, the black anodized aluminum sample, the ball-blasted stainless with CerMark sample, and the ball-blasted stainless sample performed the best. The samples were read 58%, 54%, and 35% of the number of tests in the use case.

Table 5. Summary of distance and angular testing results for each combination.

Short name	Surface finish	Material	Marking technique	Total Readings for Material	Total Read Attempts	Readability Percentage	Readings in Use Case	Read Attempts In Use Case	Readability Percentage in Use Case
Cardstock	—	Cardstock	Laser printer	462	1296	36%	292	440	66%
Black anodized aluminum	Black anodized	Aluminum	Laser	151	336	45%	56	96	58%
Ball-blasted stainless with CerMark	Ball-blasted	Stainless steel	CerMark laser marking ink	128	336	38%	52	96	54%
Ball-blasted stainless	Ball-blasted	Stainless steel	Laser	95	336	28%	34	96	35%
Aluminum	Mill finish	Aluminum	Laser	86	336	26%	29	96	30%
Dot peen stainless	Mill finish	Stainless steel	Dot peening	69	336	21%	27	96	28%
Horizontally brushed stainless	Horizontally brushed	Stainless steel	Laser	23	336	7%	12	96	13%
Vertically brushed stainless	Vertically brushed	Stainless steel	Laser	35	336	10%	6	96	6%
Mirror finish stainless	Mirror	Stainless steel	Laser	14	336	4%	5	96	5%

As depicted in Figure 12, even though the black anodized aluminum sample was read from the highest number of test orientations and performed well at 30° and 45°, it did somewhat more poorly when tested normal to the barcode surface. This, along with attachment and coefficient of expansion concerns raised by WNTI may disqualify this plate material/finish for the global cylinder identifier application. As shown in Figure 13, the ball-blasted stainless with CerMark sample demonstrated the most successful reads in orientations up to 30° away from normal. Results from the angular testing of the ball-blasted stainless sample are shown in Figure 14. This sample performed well at 0° and 45°, but the readers struggled to read the barcode at 30°. Results from angular testing of other samples are not presented due to poor readability.

Figure 12. Reader performance at different distances and angles for a 2 cm Data Matrix barcode marked on a black anodized aluminum sample. The use case range is highlighted in green. Green dots represent successful reads, and red *x*'s represent unsuccessful reads.

Figure 13. Reader performance at different distances and angles for a 2 cm Data Matrix barcode marked on a ball-blasted stainless with CerMark sample. The use case range is highlighted in green. Green dots represent successful reads, and red *x*'s represent unsuccessful reads.

Figure 14. Reader performance at different distances and angles for a 2 cm Data Matrix barcode marked on a ball-blasted stainless sample. The use case range is highlighted in green. Green dots represent successful reads, and red *x*'s represent unsuccessful reads.

2.7 DISCUSSION OF BARCODE SIZE, SURFACE TREATMENT, AND MARKING TECHNIQUE

Several sizes of 2D barcodes were tested. The 2.5 cm Data Matrix barcodes proved to be too small for the selected readers to read over the entire use case range and 5 cm barcodes were perhaps too large, but the data suggests that a 3.5 cm barcode or the similarly sized 1.4 in. barcode could be read by multiple readers from several vendors over the entire use case range (10–100 cm, ±30°).

The selected readers were also tested with 2D barcodes marked on different metals with different surface treatments and different marking techniques. The ball-blasted stainless with CerMark laser markings sample performed well in various tests and should be considered a superior choice compared to the alternatives. Although the laser etched black anodized aluminum performed well under some circumstances, it performed marginally when tested normal to the barcode surface. An aluminum identifier should likely be ruled out because of concerns WNTI working group members raised about welding an aluminum plate to the steel cylinder and questions about attachment longevity resulting from the different coefficients of expansion between the aluminum and the steel cylinder.

3. CONCLUSIONS

The ORNL team investigated DPM techniques and barcode specifications that would be applicable for a new global UF_6 cylinder identifier. That testing evaluated how several COTS DPM or barcode readers performed when varying the size of the barcode, read distance, read angle, surface finish of the material, and marking technique. This research concluded that a 1.4 in. 2D Data Matrix barcode with a 0.1 in. quiet zone would be appropriate for the machine-readable feature on a UF_6 cylinder global identifier. The testing suggests that this size barcode could supports the WNTI working group's accepted use case (i.e., multiple COTS handheld readers could read the barcode from an angle of up to 30° over the range of 10 to 100 cm).

Testing also suggested that a ball-blasted stainless steel plate with CerMark laser markings may be suitable for a UF_6 cylinder global identifiers. Barcodes marked on ball-blasted stainless with CerMark laser marking ink exhibited high contrast and were readable from a desirable range of distances and angles.

4. REFERENCES

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