WICHITA STATE UNIVERSITY

Polymer Based Additive Manufactured Qualification Guidelines

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Polymer Based Additive Manufactured Qualification Guidelines

Project Overview

Research Objectives

- Enhance the framework for the qualification of PBAM (FDM) materials including guidelines and recommendations for their characterization, testing, design, and utilization using the NCAMP process.
- Transition of the test data and guidelines generated into shared databases.

Project Deliverables

Research Outcomes

- Qualification material property test data, overview of results, and lessons learned published in an FAA technical report.
- NCAMP material property data, statistical reports, and material and process specifications published on NCAMP website.
- Test data submittal to CMH17 AM Volume.

FAA Team Members

Cindy Ashforth

Dr. Ahmet Oztekin

Kevin Stonaker

Industry Partners

Stratasys

MarkForged

Hexcel

PBAM Qualification Guidelines - History

- Ultem 9085 – PEI (polyetherimide) , F900MC+, FDM, Stratasys.
  - America Makes project – had very high CoV in the data.
  - Partnered with FAA and RP+M (Print site) to implement NCAMP approach – CoV dropped to 3-5% in most material properties.
  - Not all print machines were manufactured equally, worked with Stratasys to rectify.
  - Fully NCAMP qualified and published.
  - Testing completed 5 years after qualification completion shows that material and process have not drifted.

PBAM Qualification Guidelines - History

- Onyx FR-A/Carbon Fiber FR-A – Nylon with Longitudinal CF, Onyx 7, FFF, MarkForged.
  - Partnered with FAA and MarkForged (Print site) to implement NCAMP approach on an AM long fiber material.
  - Fiber printing was not applicable in all orientations or layers.
    - Software limitations
    - Machine limitations
  - Material is not suitable for wet conditions.
  - Intra and Inter layer instability.
  - NCAMP Qualified and Published.

PBAM Qualification Guidelines - History

- HexPEKK 100 – PEKK and CF Powder Blend, EOS P800, LPBF, Hexcel.
  - Partnered with FAA and Hexcel (Print site) to implement NCAMP approach on a LPBF polymer material.
  - Process and material are very stable – it is used in flight on many aircraft.
  - Fatigue data is available, though not part of NCAMP dataset.
  - No other print sites, no other material manufacturers, no equivalency opportunities – Due to Vertical Integration.
  - Fully NCAMP Qualified and Published.

Project P-AN8X0: Antero 800 & 840 Qualification

Project Overview

Research Objectives

- Enhance the framework for the qualification of PBAM (FDM) materials including guidelines and recommendations for their characterization, testing, design, and utilization using the NCAMP process.
- Transition of the test data and guidelines generated into shared databases such as Composite Materials Handbook-17 (CMH-17).

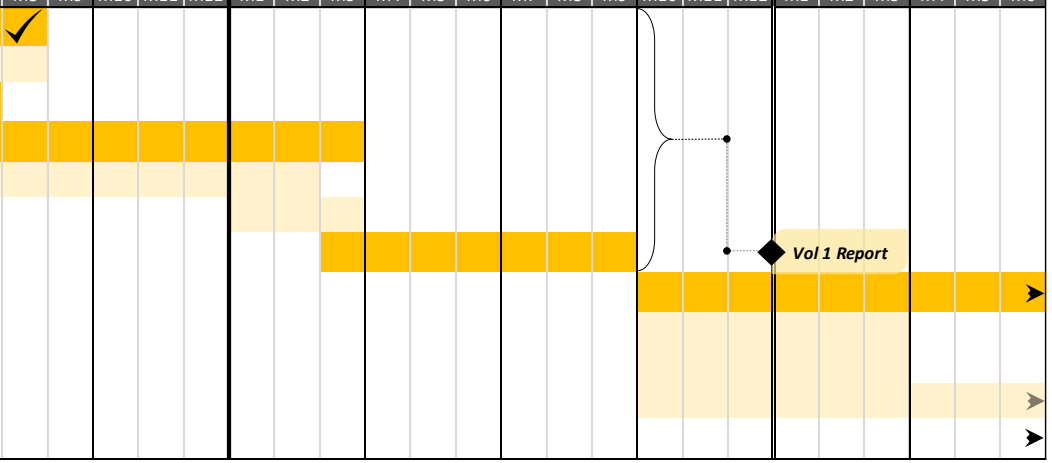
Project Deliverables

Research Outcomes

- Qualification material property test data, overview of results, and lessons learned published in an FAA technical report.
- NCAMP material property data, statistical reports, and material and process specifications published on NCAMP website.
- Using Stratasys F900 print machine.

Project Timeline – Outline of Deliverables

Main Task	Subtasks	Percent Complete
1	Coordination	100%
1.1	*Establishment of Industry Steering Committee*	
2	Material Selection and Processing Method Downselect	100%
3	Qualification Framework for PBAM Materials	57%
3.1	*Trial Testing*	
3.2	*Test Plan Development*	
4	Material and Process Specifications	0%
5	Framework Validation via PBAM Material Qualification	0%
5.1	*Raw Constituent AM Material Physical Tests*	
5.2	*AM Material Physical Testing*	
5.3	*AM Material Mechanical Property Testing*	
6	Statistical Guidelines	0%



Partners

stratasys

Antero 800 & 840

- Manufactured by Stratasys
- Replacement and/or complimentary material for Ultem 9085
- Antero 840 is a filled polymer – PEKK blend with Carbon nano-tubes (3%)
- Antero 800 is a non-filled polymer - PEKK
- Additively Manufactured using FFF, filament print process
- Increased material strength and modulus properties compared to Ultem 9085
- Designed to print on the F900, the newest single head AM print machine from Stratasys

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Participants

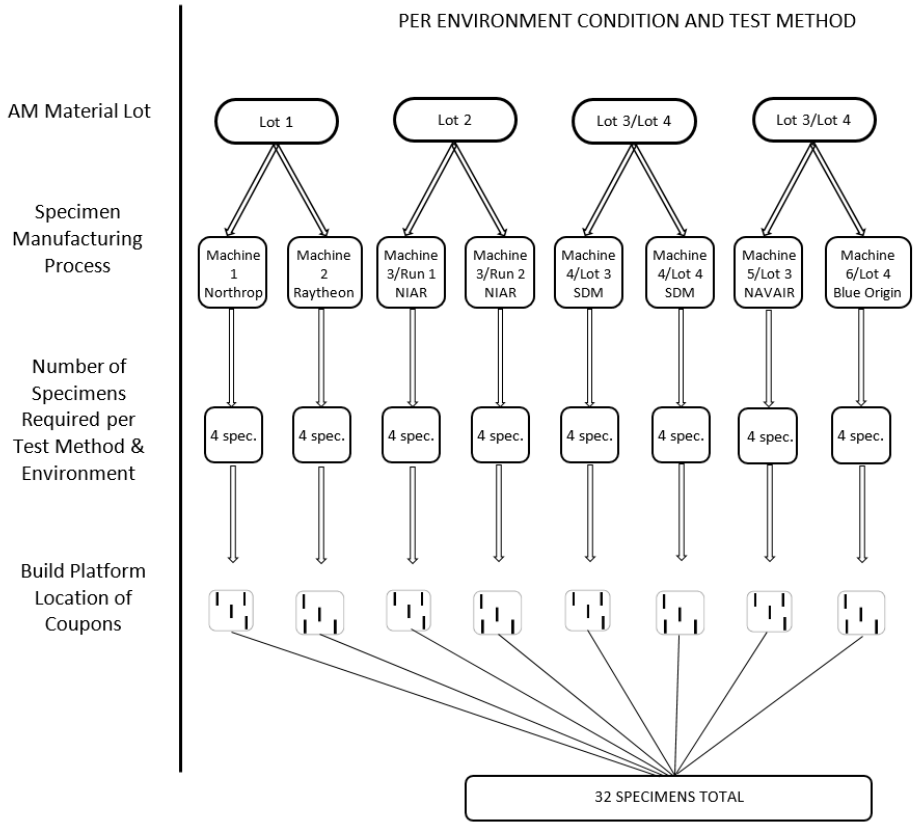
- Antero 840
- FAA
- NIAR
- Northrop Grumman
- Raytheon
- Blue Origin
- SDM (Stratasys Direct Manufacturing)
- Stratasys
- NAVAIR
- EDA

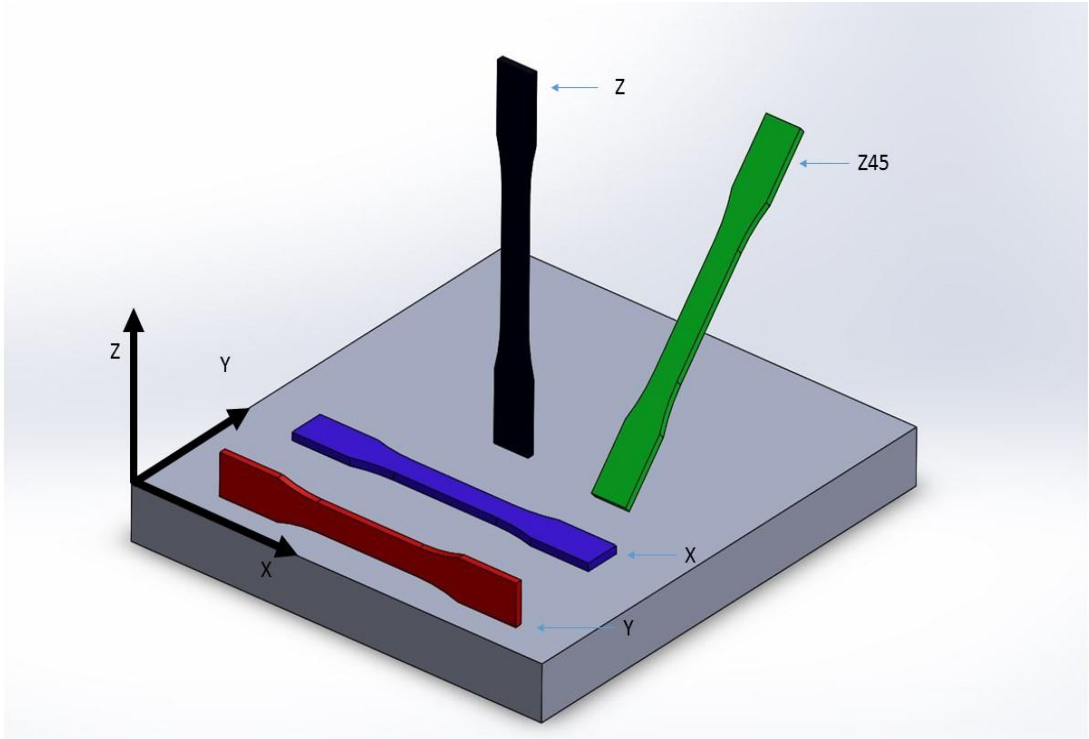
- Antero 800
- FAA
- NIAR
- Boeing
- Air Force (UDRI)
- SDM (Stratasys Direct Manufacturing)
- Stratasys
- NAVAIR
- BAE

Antero 800 & 840 Decisons

- RTA: 70F+/-10F
- RTW: 70F+/-10F
- CTA: -65F will be used for Antero 800, -95F will be used for Antero 840
- ETA: 250F will be used for both programs.
- ETW: 180F will be used for both programs.
- Raster Direction: +/-45 will be used for both programs.
- Conditioning per ASTM D5229; 180F, 85%RH, 0.02% saturation
- Slicer and machine operation software version will be set at a minimum. If your version changes you must meet material specification limits to show adequacy of change. If slicer software has a version change it will be tested in the CMB Comparison Tool, if this shows a certain % change in the infill, then a manual review with the Stratasys team takes place, if a possible material performance change is found, then mechanical testing occurs with reporting. Operational software will be reviewed annually with same CMB Comparison Tool. This will be audited as part of the NCAMP audit procedures. Any changes that are deemed significant will follow the NCAMP ACN process. Hardware changes will follow the same process.
- Coupons will be tested two weeks after printing unless conditioning or other post processing work needs to take place.
- All notches and holes will be machined.
- Fatigue Testing will replace OHC and FHC.

- Test Matrix Build and coupon build orientations





Test Matrix - Feedstock

Property	Method	Min Replicates per Resin Line
Flammability Drip Time	FAR 25.853 (D) Appendix F, Part IV	2
Flammability Extinguishing Time	FAR 25.853 (A), Appendix F, Part I, (a), 1, (i): 60 sec	2
Flammability Burn Length	FAR 25.853 (A), Appendix F, Part I, (a), 1, (i): 60 sec	2
NBS Smoke and Density	FAR25.853 (D), Appendix F, PART V	2
Heat Release Peak	FAR 25.853 (D) Appendix F, Part IV	2
MFR 380°C @ 1.2KG	ASTM D1238	2

Test Matrix - Filament (Material Spec)

Filament Production

Property	Number of Replicates
Diameter	Continuously
Ovality	Continuously

Filament Canisters

Property	Number of Replicates
Moisture	First, middle (roughly), and end of batch
Melt Flow	First, middle (roughly), and end of batch
Pull Force	First, middle (roughly), and end of batch

Test Matrix - Printed Material Physical Properties

Property	Condition/Method (Note 1)
Thickness	ASTM D3171-15/or applicable mechanical test method.
Density	ASTM D792-13
Photomicrograph	CP6101 and CP6102
CTE by TMA	ASTM E228/E831
Glass Transition Temperature, Tg by DMA flexural loading	Dry and Wet – ASTM D7028
Thermal Conductivity	ASTM E1530
Specific Heat	ASTM E1269
Flammability Drip Time	FAR 25.853 (D) Appendix F, Part IV
Flammability Extinguishing Time	FAR 25.853 (A), Appendix F, Part I, (a), 1, (i): 60 sec
Flammability Burn Length	FAR 25.853 (A), Appendix F, Part I, (a), 1, (i): 60 sec
NBS Smoke and Density	FAR 25.853 (D), Appendix F, PART V
Heat Release Peak	FAR 25.853 (D) Appendix F, Part IV

Test Matrix – Printed Material Mechanical Properties

Test Type and Direction	Property	Number of Batches x Number of Runs x Number of Coupons					
		Test Temperature/Moisture Condition					
		CTA	RTA	ETA1	RTW	ETW1	
ASTM D638 (type 1) Tension X (2)	Strength and Modulus	5x2x4	5x2x4		1x2x4 (5)	5x2x4	
ASTM D638 (type 1) Tension Y (2)	Strength and Modulus	5x2x4	5x2x4		1x2x4 (5)	5x2x4	
ASTM D638 (type 1) Tension Z (2)	Strength and Modulus	5x2x4	5x2x4		1x2x4 (5)	5x2x4	
ASTM D638 (type 1) Tension Z (45) (2)	Strength and Modulus	5x2x4	5x2x4		1x2x4 (5)	5x2x4	
ASTM D695 prism 1" Compression X (1)(2)	Strength and Modulus	5x2x4	5x2x4	1x2x4	1x2x4 (5)	5x2x4	
ASTM D695 prism 1" Compression Y (1)(2)	Strength and Modulus	5x2x4	5x2x4	1x2x4	1x2x4 (5)	5x2x4	
ASTM D695 prism 1" Compression Z (1)(2)	Strength and Modulus	5x2x4	5x2x4	1x2x4	1x2x4 (5)	5x2x4	
ASTM D695 prism 1" Compression Z (45) (1)(2)	Strength and Modulus	5x2x4	5x2x4	1x2x4	1x2x4 (5)	5x2x4	
ASTM D790 Flex X (2)(6)	Strength and Modulus	5x2x4	5x2x4			5x2x4	
ASTM D790 Flex Y (2)(6)	Strength and Modulus	5x2x4	5x2x4			5x2x4	
ASTM D790 Flex Z (2)(6)	Strength and Modulus	5x2x4	5x2x4			5x2x4	
ASTM D790 Flex Z (45) (2)(6)	Strength and Modulus	5x2x4	5x2x4			5x2x4	
ASTM D5379 V-notch In-Plane Shear X (2)(3)(4)	Strength and Modulus	5x2x4	5x2x4		1x2x4 (5)	5x2x4	

Test Type	Test Type (6)	Property	Number of Batches x Number of Machines x Number of Coupons		
			Test Temperature/Moisture Condition		
			CTD	RTD	ETW1
OHT	ASTM D5766 Open Hole Tension X (1)	Strength	5x2x4	5x2x4	5x2x4
OHT	ASTM D5766 Open Hole Tension Y (1)	Strength	5x2x4	5x2x4	5x2x4
OHT	ASTM D5766 Open Hole Tension Z (1)	Strength	5x2x4	5x2x4	5x2x4
OHT	ASTM D5766 Open Hole Tension Z (45) (1)	Strength	5x2x4	5x2x4	5x2x4
FHT	ASTM D6742 Filled Hole Tension X (2)	Strength	5x2x4	5x2x4	5x2x4
FHT	ASTM D6742 Filled Hole Tension Y (2)	Strength	5x2x4	5x2x4	5x2x4
FHT	ASTM D6742 Filled Hole Tension Z (2)	Strength	5x2x4	5x2x4	5x2x4
FHT	ASTM D6742 Filled Hole Tension Z (45) (2)	Strength	5x2x4	5x2x4	5x2x4
Fatigue	Fatigue Testing: D638 Type 1, X, E466 load control	5 stress levels		15	15
Fatigue	Fatigue Testing: D638 Type 1 Y, E466 load control	5 Stress levels		15	15
Fatigue	Fatigue Testing: D638 Type 1, Z , E466 load control	5 Stress levels		15	15
Fatigue	Fatigue Testing: D638 Type 1, Z45, E466 load control	5 stress levels		15	15
SSB	ASTM D5961 Single Shear Bearing X (4)	Strength & Deformation		5x2x4	5x2x4
SSB	ASTM D5961 Single Shear Bearing Y (4)	Strength & Deformation		5x2x4	5x2x4
SSB	ASTM D5961 Single Shear Bearing Z (4)	Strength & Deformation		5x2x4	5x2x4
SSB	ASTM D5961 Single Shear Bearing Z (45) (4)	Strength & Deformation		5x2x4	5x2x4

Test Matrix – Printed Material Fluid Sensitivity

ASTM D638
Type 1 Coupons

Extended Contact:	Exposure	Test Condition	Code
100 Low Lead Aviation Fuel (ASTM D910)	90 days min. @ 70°F±10°F	70°F	TFS11RT
	90 days min. @ 70°F±10°F	180°F	TFS11ET
ASTM D1655 Jet A Fuel (other jet fuel may be used but its type must be reported)	90 days min. @ 70°F±10°F	70°F	TFS12RT
	90 days min. @ 70°F±10°F	180°F	TFS12ET
MIL-PRF-5606 Hydraulic Oil	90 days min. @ 70°F±10°F	70°F	TFS13RT
	90 days min. @ 70°F±10°F	180°F	TFS13ET
MIL-PRF-83282 Hydraulic Oil	90 days min. @ 70°F±10°F	70°F	TFS14RT
	90 days min. @ 70°F±10°F	180°F	TFS14ET
MIL-PRF-7808 Engine Oil	90 days min. @ 70°F±10°F	70°F	TFS15RT
	90 days min. @ 70°F±10°F	180°F	TFS15ET
MIL-PRF-23699, Class STD Engine Oil	90 days min. @ 70°F±10°F	70°F	TFS16RT
	90 days min. @ 70°F±10°F	180°F	TFS16ET
Sea Water (ASTM D1141 or equiv.)	90 days min. @ 70°F±10°F	70°F	TFS17RT
	90 days min. @ 70°F±10°F	180°F	TFS17ET
Skydrol LD-4 (SAE AS1241, Type IV, Class 1)	90 days min. @ 70°F±10°F	70°F	TFS18RT
	90 days min. @ 70°F±10°F	180°F	TFS18ET
50% Water with 50% Skydrol LD-4 (SAE AS1241, Type IV, Class 1)	90 days min. @ 70°F±10°F	70°F	TFS19RT
	90 days min. @ 70°F±10°F	180°F	TFS19ET
Short Duration Contact:			
MEK washing fluid. ASTM D740	90 minutes min. @ 70°F±10°F	70°F	TFS21RT
	90 minutes min. @ 70°F±10°F	180°F	TFS21ET
Polypropylene Glycol Deicer (Type I) SAE AMS 1424	90 minutes min. @ 70°F±10°F	70°F	TFS22RT
	90 minutes min. @ 70°F±10°F	180°F	TFS22ET
Isopropyl Alcohol Deicing Agent (TT-I-735)	48±4 hours @70°F±10°F	70°F	TFS23RT
	48±4 hours @70°F±10°F	180°F	TFS23ET
Control Tests:			
Distilled Water	90 days min. at 70°F±10°F	70°F	TFS31RT
	90 days min. at 70°F±10°F	180°F	TFS31ET
Dry	Dry per section 6.1	70°F	TFS32RT
	Dry per section 6.1	180°F	TFS32ET
85% Relative Humidity	Per section 6.1	70°F	TFS33RT
	Per section 6.1	180°F	TFS33ET

Current progress: Antero 800

Air Force/UDRI

- All mechanical testing has been completed, and data is available.

NAVAIR

- ETW coupons are now in conditioning.
- Ambient coupons are ready to be tested, waiting to be scheduled

NIAR

- Coupon conformity has been completed for the ETW coupons (R1 and R2) and are placed in the conditioning chamber
- R1 and R2 CTA coupons are due to be out of machining on 5/4 and done with QC on 5/20
- R1 and R2, RTA and ETA are still being printed. Issues with printer were resolved by Stratasys.

Boeing

- Coupons are due out of QC on 5/5. Once that is done, conformity of the coupons show follow the same week.

SDM

- Coupons from batch C that are CTA, RTA and ETA are still in database
- Coupons from batch D and ETW of batch C will complete QC on 5/20.

BAE

- Changed machines due to printer breakdown and production schedule. More updates to follow

Current Progress: Antero 840

NIAR

- All coupons are ready for testing except ETW. Some of them have been tested and some are in queue to be tested

NGC

- Coupons are in testing for ambient, and in conditioning for ETW. Some test methods have been tested, and some are on queue to be tested

RAYTHEON

- Almost all testing is completed for all ambient environments except ETW.

BLUE ORIGIN

- Ambient coupons are in queue for testing. ETW coupons are in the chamber for conditioning.

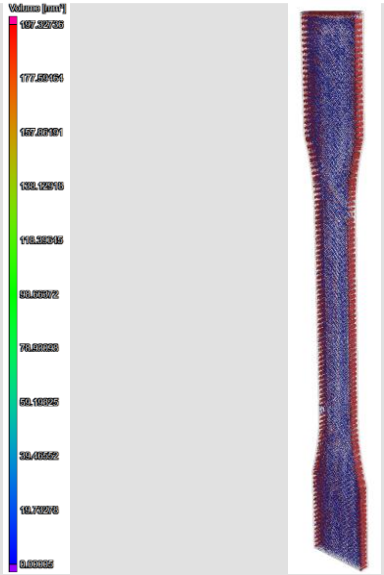
NAVAIR

- All coupons from all environments are complete with testing and are in data reduction.

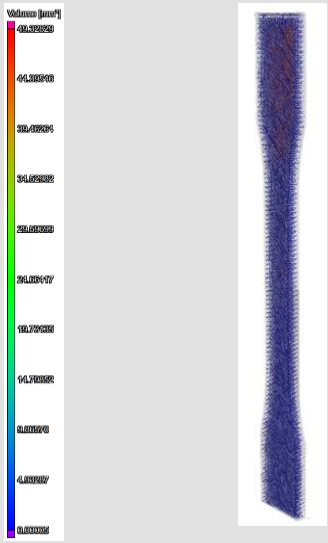
SDM

- All coupons are due out of quality control on 5/9. The coupons will go through the conformity process right after.

X-Ray CT Scan, Antero 800

NTPAM8400Q1-STR-800CN-NAV-C-M5-XY-T-11-ETW-1	Porosity	Inclusion
		
XCT Parameters **Voltage:** 120 kV **Current:** 225 mA **Scan time:** 2hour 59mins **Resolution:** 25.582 microns	**Analysis Statistics** **Defect Volume :** 297.34097 mm^3 **Material Volume :** 7715.16113 mm^3 **Defect Volume Ratio :** 3.71096%	**Analysis Statistics** **Defect Volume :** 0 mm^3 **Material Volume :** 7897.14404 mm^3 **Defect Volume Ratio :** 0%

X-Ray CT Scan, Antero 840

NTP8400AMQ1-STR-840CN-NIA-B-M3R1-XY-T-11-RTA-1	Porosity	Inclusion
		
XCT Parameters **Voltage**: 120 kV **Current**: 225 mA **Scan time**: 2h59mins **Resolution**: 25.591 microns	**Analysis Statistics** **Defect Volume** : 344.79114 mm^3 **Material Volume** : 7878.14258 mm^3 **Defect Volume Ratio** : 4.19304 %	**Analysis Statistics** **Defect Volume** : 0 mm^3 **Material Volume** : 8208.99219 mm^3 **Defect Volume Ratio** : 0%

Antero 800, Specific Density testing, ASTM D792

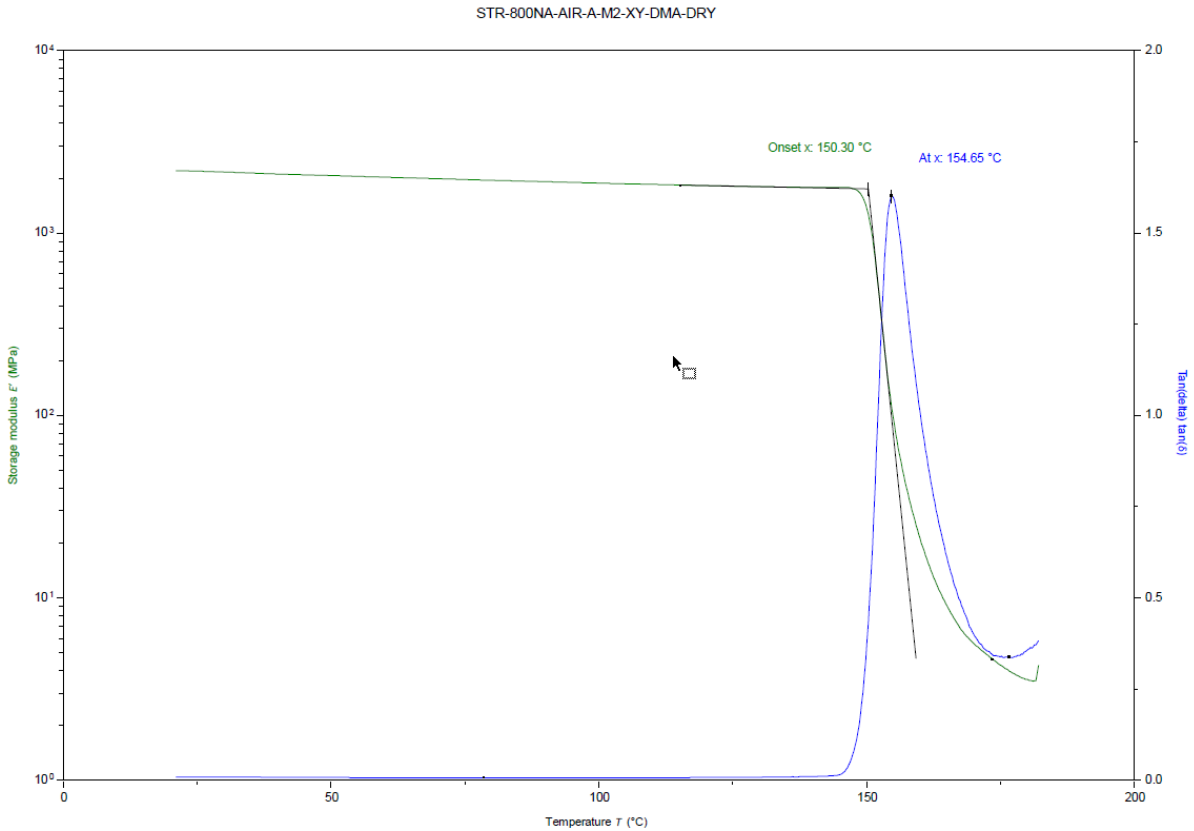
D792-20 Specific Gravity (Relative Density)							
Sample Name	W1 [g]	W2 [g]	Water Temp. [°C]	Water Density at Temp. [g/cc]	Specific Gravity	Specimen Density [g/cc]	Specimen Density [lbm/in3]
NTPAM8000Q1-STR-800NA-AIR-A-M2-ZX-DEN-RTA-1	2.6983	0.5437	22.5000	0.99766	1.2523	1.2494	0.0451
NTPAM8000Q1-STR-800NA-AIR-A-M2-Z45-DEN-RTA-1	2.6085	0.5012	22.5000	0.99766	1.2378	1.2349	0.0446
NTPAM8000Q1-STR-800NA-AIR-A-M2-XY-DEN-RTA-1	2.5588	0.5031	22.4000	0.99769	1.2447	1.2419	0.0449
NTPAM8000Q1-STR-800NA-AIR-A-M2-XZ-DEN-RTA-1	2.6519	0.5318	22.4000	0.99769	1.2508	1.2479	0.0451
				AVERAGE (composite)	1.2464	1.2435	0.0449
				STANDARD DEVIATION	0.0066	0.0066	0.0002
				COEFF. OF VARIATION	0.5303	0.5306	0.5306
				Minimum	1.2378	1.2349	0.0446
				Maximum	1.2523	1.2494	0.0451
				Number of Specimens	4	4	4

Antero 840, Specific Density testing, ASTM D792

D792-20 Specific Gravity (Relative Density)							
Sample Name	W1 [g]	W2 [g]	Water Temp. [°C]	Water Density at Temp. [g/cc]	Specific Gravity	Specimen Density [g/cc]	Specimen Density [lbm/in3]
NTPAM8400Q1-STR-840CN-NIA-B-M3R2-Z45-DEN-RTA-1	2.6062	0.5370	23.1000	0.99752	1.2595	1.2564	0.0454
NTPAM8400Q1-STR-840CN-NIA-B-M3R2-XZ-DEN-RTA-1	2.6352	0.5576	23.0000	0.99755	1.2684	1.2653	0.0457
NTPAM8400Q1-STR-840CN-NIA-B-M3R2-XY-DEN-RTA-1	2.6048	0.5530	22.8000	0.99759	1.2695	1.2665	0.0458
NTPAM8400Q1-STR-840CN-NIA-B-M3R2-ZX-DEN-RTA-1	2.6066	0.5399	22.8000	0.99759	1.2612	1.2582	0.0455
NTPAM8400Q1-STR-840CN-NIA-B-M3R1-XZ-DEN-15-RTA-1	2.6501	0.5522	22.7000	0.99762	1.2632	1.2602	0.0455
NTPAM8400Q1-STR-840CN-NIA-B-M3R1-XY-DEN-15-RTA-1	2.6130	0.5305	22.7000	0.99762	1.2547	1.2518	0.0452
NTPAM8400Q1-STR-840CN-NIA-B-M3R1-Z45-DEN-15-RTA-1	2.6093	0.5296	22.6000	0.99764	1.2547	1.2517	0.0452
NTPAM8400Q1-STR-840CN-NIA-B-M3R1-ZX-DEN-15-RTA-1	2.6177	0.5381	22.5000	0.99766	1.2588	1.2558	0.0454
				AVERAGE (composite)	1.2613	1.2582	0.0455
				STANDARD DEVIATION	0.0056	0.0055	0.0002
				COEFF. OF VARIATION	0.4428	0.4407	0.4407
				Minimum	1.2547	1.2517	0.0452
				Maximum	1.2695	1.2665	0.0458
				Number of Specimens	8	8	8

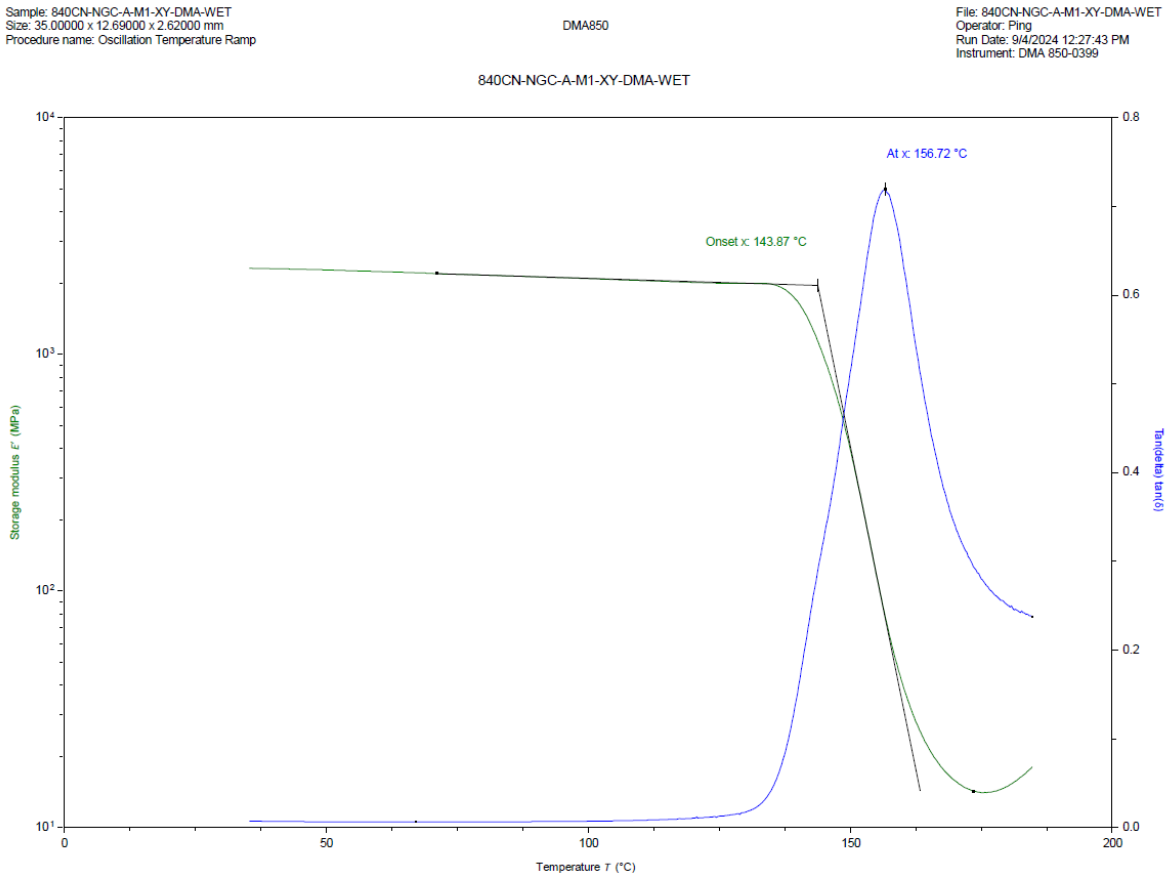
ASTM D7024, Dry DMA Testing, Antero 800

DMA Results Summary NCAMP Antero 800 DMA Dry				
Sample ID	Onset Storage Modulus		Peak of Tangent Delta	
	T_g [°C]	T_g [°F]	T_g [°C]	T_g [°F]
STR-800NA-AIR-A-M2-XY-DMA-DRY	150.30	302.54	154.65	310.37
STR-800NA-AIR-A-M2-XZ-DMA-DRY	149.38	300.88	154.20	309.56
STR-800NA-AIR-A-M2-ZX-DMA-DRY	150.57	303.03	155.25	311.45
STR-800NA-AIR-A-M2-Z45-DMA-DRY	149.98	301.96	154.72	310.50
Average	150.06	302.10	154.71	310.47
Standard Deviation	0.51	0.92	0.43	0.77



ASTM D7024, Wet DMA Testing, Antero 800

DMA Results Summary NCAMP Antero 840 DMA Wet				
Sample ID	Onset Storage Modulus		Peak of Tangent Delta	
	T_g [°C]	T_g [°F]	T_g [°C]	T_g [°F]
840CN-NGC-A-M1-XY-DMA-WET	143.87	290.97	156.72	314.10
840CN-NGC-A-M1-XZ-DMA-WET	141.82	287.28	156.86	314.35
840CN-NGC-A-M1-ZX-DMA-WET	142.40	288.32	156.88	314.38
840CN-NGC-A-M1-Z45-DMA-WET	143.98	291.16	156.82	314.28
Average	143.02	289.43	156.82	314.28
Standard Deviation	1.08	1.94	0.07	0.13

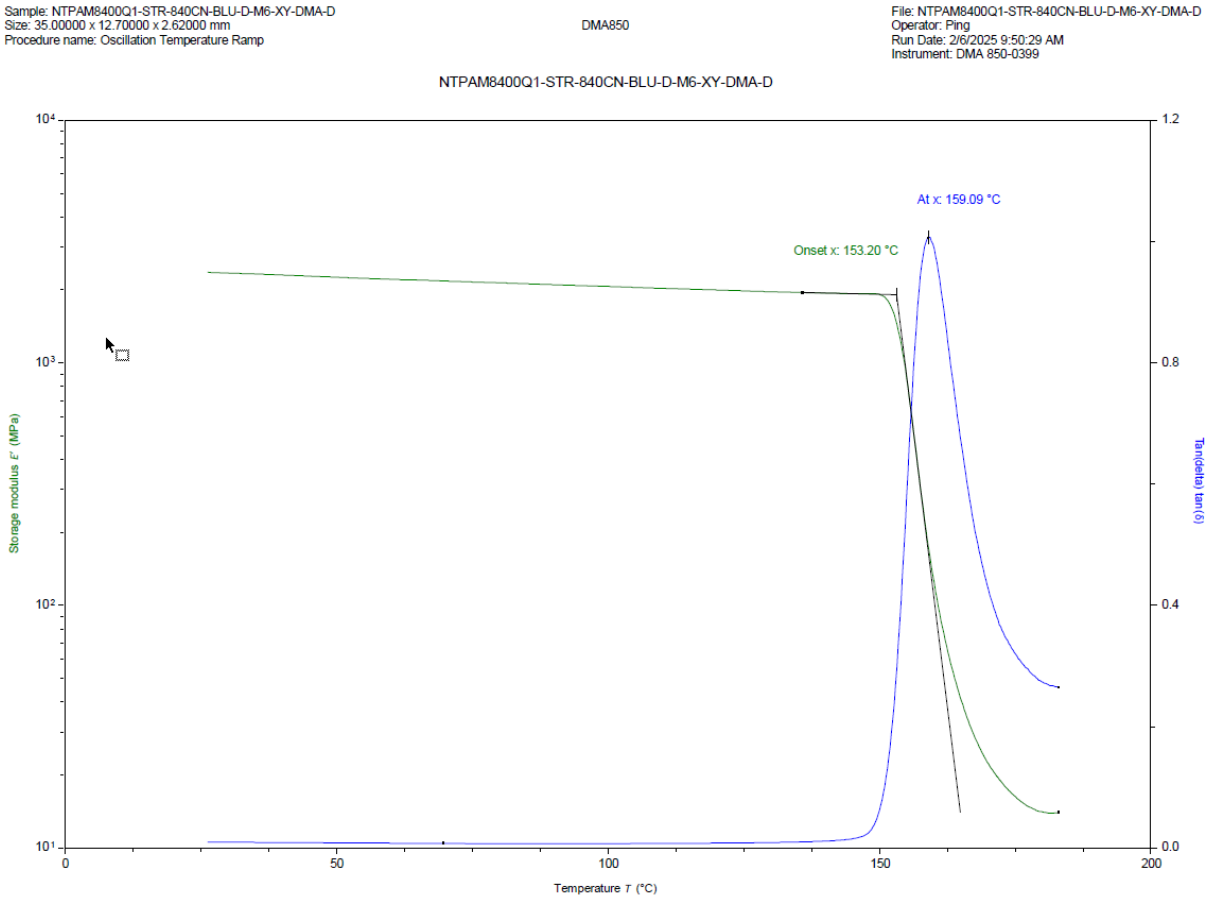


ASTM D7024, Dry DMA Testing, Antero 840

DMA Results Summary

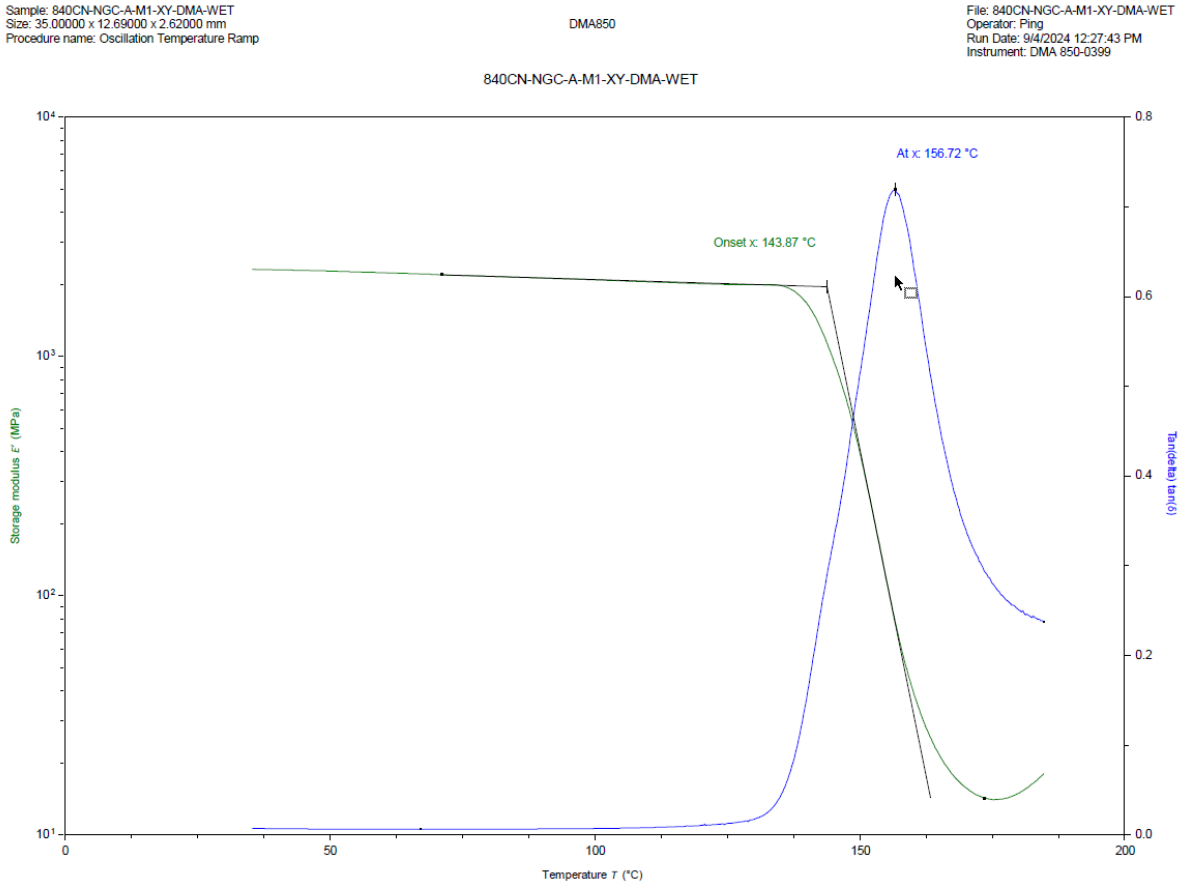
Stratasys Antero 840 DMA Dry

Sample ID	Onset Storage Modulus		Peak of Tangent Delta	
	T_g [°C]	T_g [°F]	T_g [°C]	T_g [°F]
NTPAM8400Q1-STR-840CN-BLU-D-M6-XY-DMA-D	153.20	307.76	159.09	318.36
NTPAM8400Q1-STR-840CN-BLU-D-M6-XZ-DMA-D	152.16	305.89	158.28	316.90
NTPAM8400Q1-STR-840CN-BLU-D-M6-ZX-DMA-D	152.54	306.57	160.57	321.03
NTPAM8400Q1-STR-840CN-BLU-D-M6-Z45-DMA-D	152.68	306.82	161.48	322.66
NTPAM8400Q1-STR-840CN-NAV-C-M5-XY-DMA-D	154.17	309.51	160.29	320.52
NTPAM8400Q1-STR-840CN-NAV-C-M5-XZ-DMA-D	153.30	307.94	159.16	318.49
NTPAM8400Q1-STR-840CN-NAV-C-M5-ZX-DMA-D	153.26	307.87	160.49	320.88
NTPAM8400Q1-STR-840CN-NAV-C-M5-Z45-DMA-D	153.37	308.07	161.86	323.35
NTPAM8400Q1-STR-840CN-NIA-B-M3R1-XY-DMA-D	151.72	305.10	158.39	317.10
NTPAM8400Q1-STR-840CN-NIA-B-M3R1-XZ-DMA-D	151.73	305.11	158.44	317.19
NTPAM8400Q1-STR-840CN-NIA-B-M3R1-ZX-DMA-D	152.29	306.12	161.22	322.20
NTPAM8400Q1-STR-840CN-NIA-B-M3R1-Z45-DMA-D	152.07	305.73	161.79	323.22
NTPAM8400Q1-STR-840CN-NIA-B-M3R2-XY-DMA-D	152.98	307.36	159.66	319.39
NTPAM8400Q1-STR-840CN-NIA-B-M3R2-XZ-DMA-D	153.08	307.54	159.43	318.97
NTPAM8400Q1-STR-840CN-NIA-B-M3R2-ZX-DMA-D	152.85	307.13	160.13	320.23
NTPAM8400Q1-STR-840CN-NIA-B-M3R2-Z45-DMA-D	153.40	308.12	162.47	324.45
NTPAM8400Q1-STR-840CN-RAY-A-M2-XY-DMA-D	153.49	308.28	158.91	318.04
NTPAM8400Q1-STR-840CN-RAY-A-M2-XZ-DMA-D	153.67	308.61	159.09	318.36
NTPAM8400Q1-STR-840CN-RAY-A-M2-ZX-DMA-D	153.34	308.01	159.45	319.01
NTPAM8400Q1-STR-840CN-RAY-A-M2-Z45-DMA-D	153.17	307.71	160.52	320.94
Average	152.92	307.26	160.04	320.06
Standard Deviation	0.66	1.19	1.25	2.25



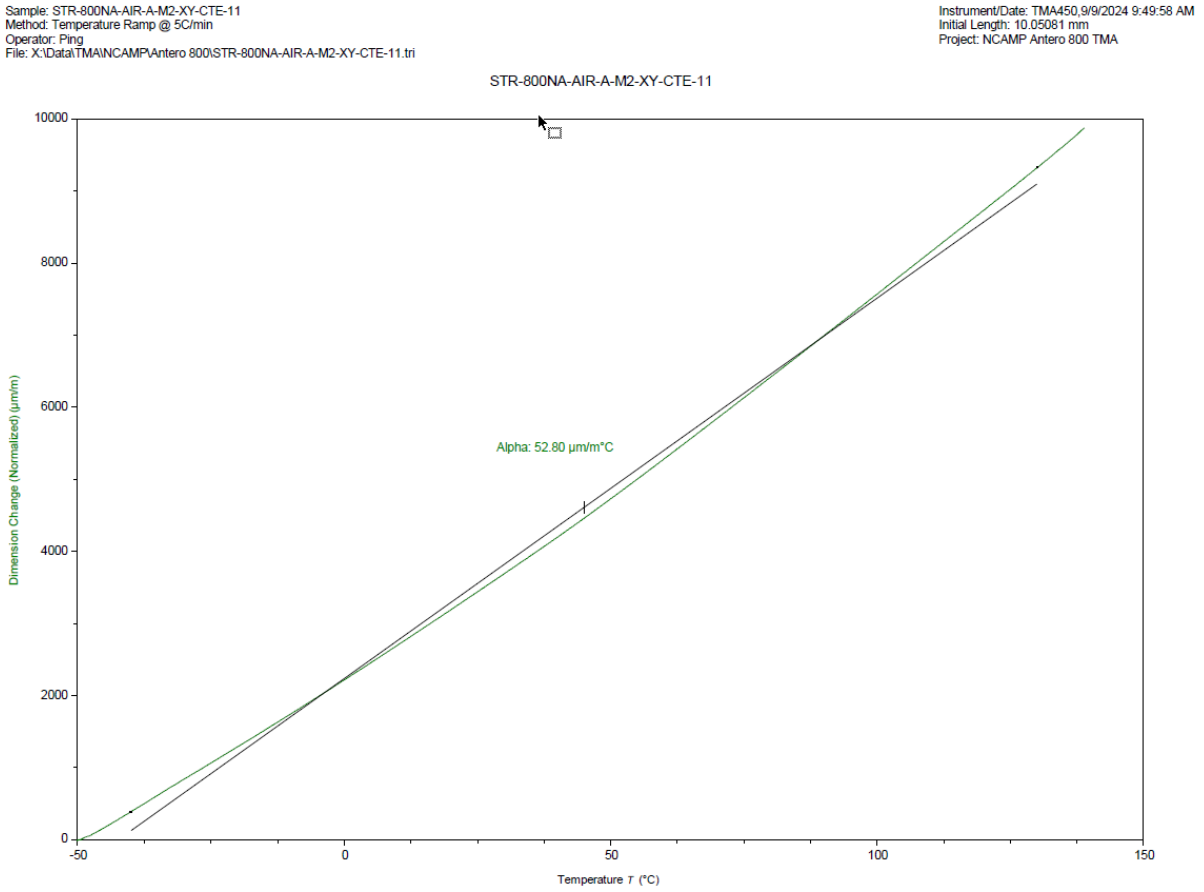
ASTM D7024, Wet DMA Testing, Antero 840

DMA Results Summary NCAMP Antero 840 DMA Wet				
Sample ID	Onset Storage Modulus		Peak of Tangent Delta	
	T_g [°C]	T_g [°F]	T_g [°C]	T_g [°F]
840CN-NGC-A-M1-XY-DMA-WET	143.87	290.97	156.72	314.10
840CN-NGC-A-M1-XZ-DMA-WET	141.82	287.28	156.86	314.35
840CN-NGC-A-M1-ZX-DMA-WET	142.40	288.32	156.88	314.38
840CN-NGC-A-M1-Z45-DMA-WET	143.98	291.16	156.82	314.28
Average	143.02	289.43	156.82	314.28
Standard Deviation	1.08	1.94	0.07	0.13



ASTM E831 TMA testing, Antero 800

TMA Results		
NCAMP Antero 800 TMA		
Sample ID	**Coefficient of Thermal Expansion**	
	α [µm/(m·°C)]	***α [µin/(in·°F)]***
STR-800NA-AIR-A-M2-XY-CTE-11	52.80	29.33
STR-800NA-AIR-A-M2-XZ-CTE-13	51.03	28.35
STR-800NA-AIR-A-M2-ZX-CTE-14	50.82	28.23
STR-800NA-AIR-A-M2-Z45-CTE-15	50.68	28.16
Average	51.33	28.52
St. Dev.	0.99	0.55



ASTM E831 TMA testing, Antero 840

TMA Results		
Stratasys Antero 840 TMA		
Sample ID	**Coefficient of Thermal Expansion**	
	α [µm/(m·°C)]	***α [µin/(in·°F)]***
NTPAM8400Q1-STR-840CN-NIA-B-M3R1-XY-TMA	49.61	27.56
NTPAM8400Q1-STR-840CN-NIA-B-M3R1-XZ-TMA	49.69	27.61
NTPAM8400Q1-STR-840CN-NIA-B-M3R1-ZX-TMA	58.00	32.22
NTPAM8400Q1-STR-840CN-NIA-B-M3R1-Z45-TMA	53.27	29.59

Test Parameters:

Instrument: TA Instruments Discovery TMA 450

Test Fixture: Expansion Probe

Test Method: ASTM E831

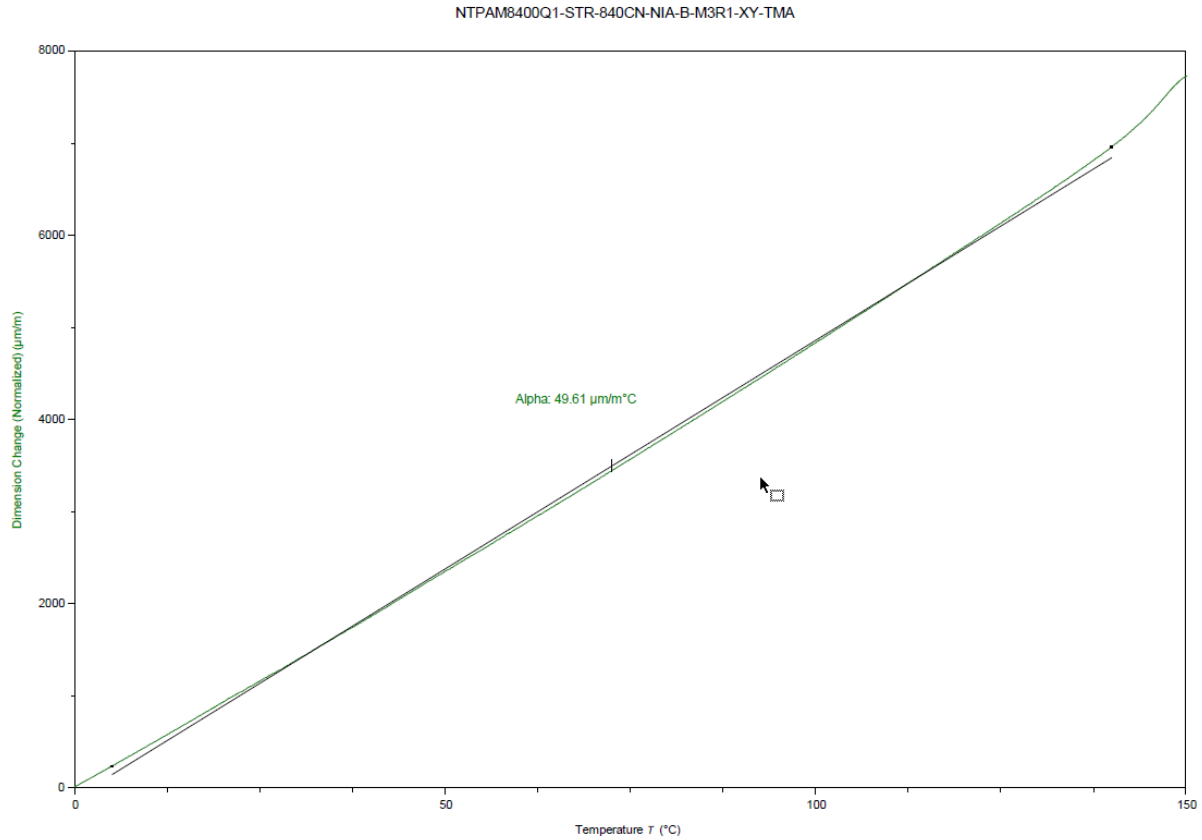
Controlled Force: 0.05 N

Ramp Rate: 5ºC/min

Temperature Range: 0ºC to 150ºC

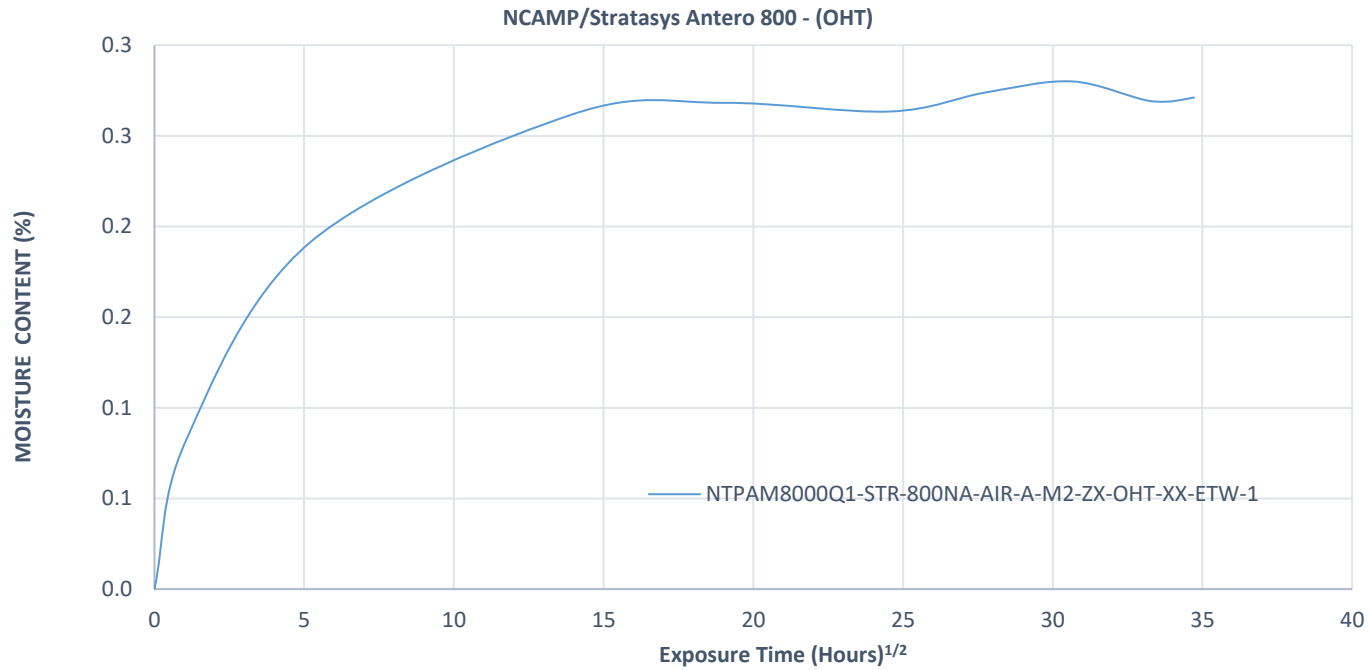
Sample: NTPAM8400Q1-STR-840CN-NIA-B-M3R1-XY-TMA
Method: Temperature Ramp @ 5C/min
Operator: Ping
File: X:\Data\TMA\Stratasys\2025\Antero 840\NTPAM8400Q1-STR-840CN-NIA-B-M3R1-XY-TMA.tri

Instrument/Date: TMA450,1/31/2025 12:26:43 PM
Initial Length: 10.12548 mm
Project: Stratasys Antero 840 TMA



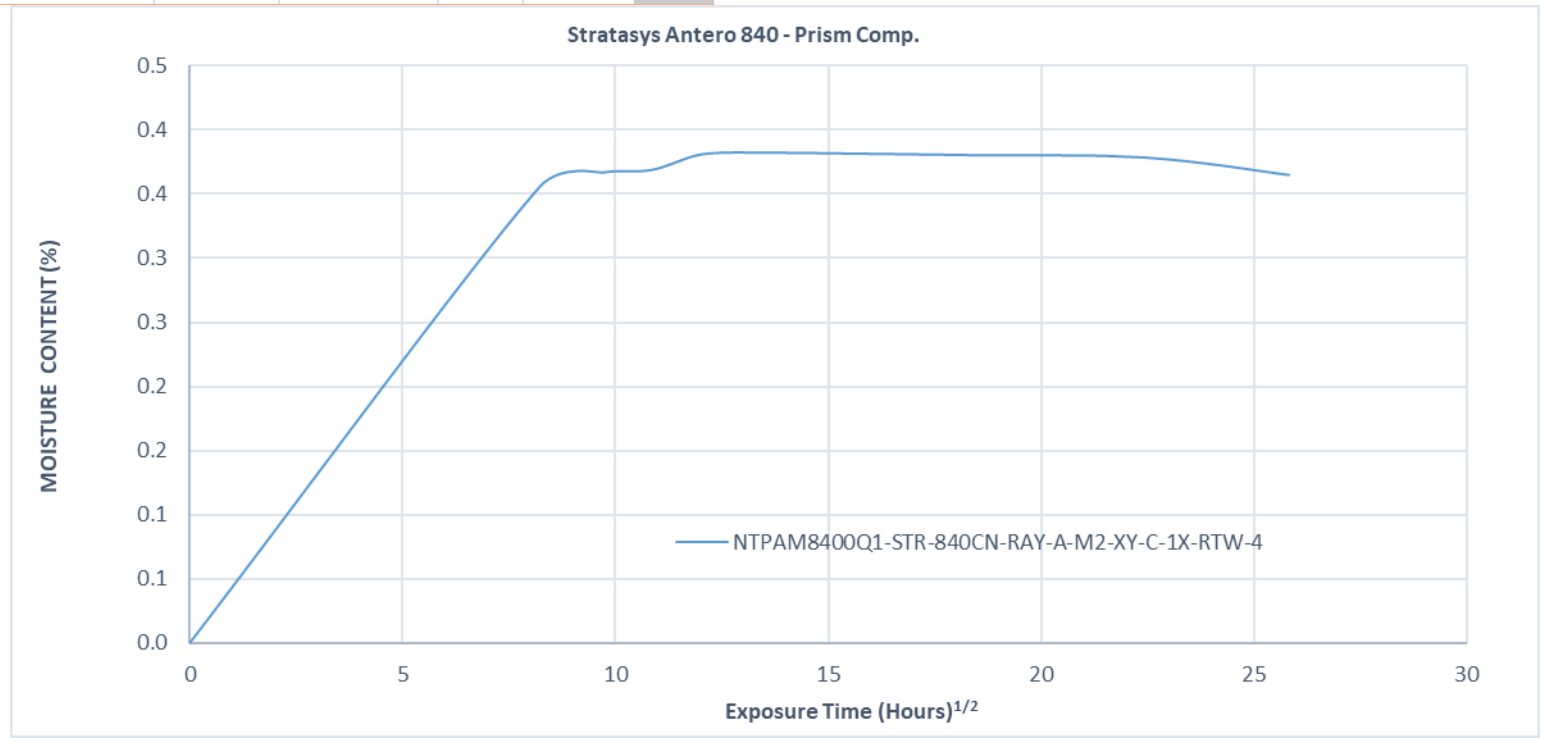
ASTM D5229 Wet Coupons saturation, Antero 800

Date/Time	Time	Period	Time^1/2	Weight (g)	%WG (Total)	Δ(%WGT)/Δ(T)	Criteria	Normalized	Criteria
	days	days	hours^1/2	NTPAM8000Q1-STR-800NA-AIR-A-M2-ZX-OHT-XX-ETW-1	NTPAM8000Q1-STR	NTPAM8000Q1-STR-800	<0.02	7 days	met
9/26/2024 8:09	0.000		0.000	31.3206	0.00000				
9/26/2024 9:14	0.045	0.045	1.038	31.3461	0.08142	1.81298	**0.08142**	**12.69083**	N/A
9/27/2024 11:10	1.126	1.081	5.198	31.3805	0.19125	0.10161	**0.10983**	**0.71128**	NO
10/4/2024 10:53	8.114	6.988	13.955	31.4026	0.26181	0.01010	**0.07056**	**0.07068**	NO
10/11/2024 9:57	15.075	6.961	19.021	31.4046	0.26819	0.00092	**0.00639**	**0.00642**	NO
10/21/2024 11:13	25.128	10.053	24.558	31.4031	0.26340	-0.00048	**-0.00479**	**-0.00333**	YES
10/28/2024 11:17	32.131	7.003	27.769	31.4064	0.27394	0.00150	**0.01054**	**0.01053**	YES
11/4/2024 12:06	39.165	7.034	30.659	31.4083	0.28001	0.00086	**0.00607**	**0.00604**	YES
11/11/2024 11:29	46.139	6.974	33.277	31.4049	0.26915	-0.00156	**-0.01086**	**-0.01090**	YES
11/15/2024 13:31	50.224	4.084	34.718	31.4055	0.27107	0.00047	**0.00192**	**0.00328**	YES
REMOVED 11.15.2024 SP									

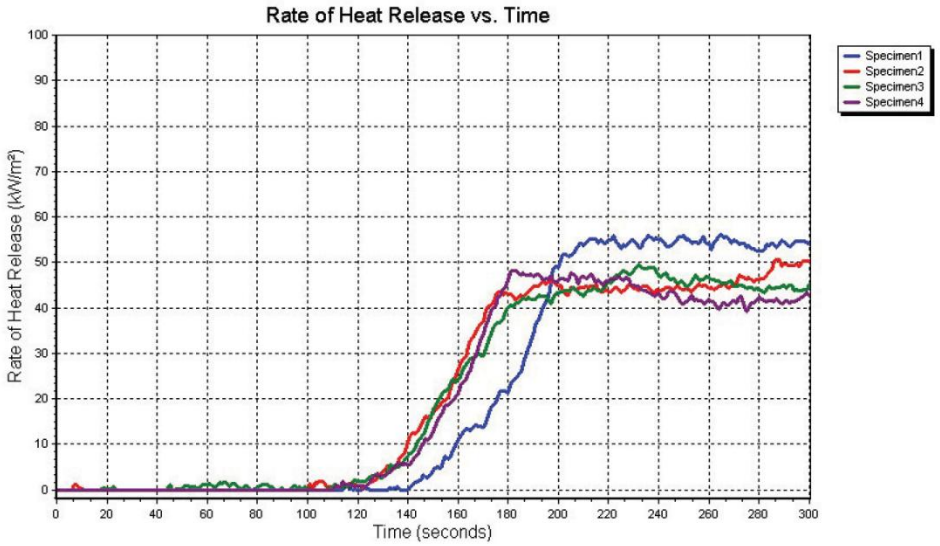


ASTM D5229 Wet Coupons saturation, Antero 840

Date/Time	Time	Period	Time^1/2	Weight (g)	%WG (Total)	Δ(%WGT)/Δ(T)	Criteria	Normalized	Criteria
	days	days	hours^1/2	NTPAM8400Q1-STR-840CN-RAY-A-M2-XY-C-1X-RTW-4	NTPAM8400Q1-STI	NTPAM8400Q1-STR-840	<0.02	7 days	met
11/15/2024 15:49	0.000		0.000	5.1570	0.00000				
11/18/2024 11:10	2.806	2.806	8.207	5.1753	0.35486	0.12644	**0.35486**	**0.88510**	N/A
11/19/2024 14:13	3.933	1.127	9.716	5.1759	0.36649	0.01032	**0.01163**	**0.07227**	NO
11/20/2024 13:22	4.898	0.965	10.842	5.1760	0.36843	0.00201	**0.00194**	**0.01407**	NO
11/21/2024 14:10	5.931	1.033	11.931	5.1766	0.38007	0.01126	**0.01163**	**0.07880**	NO
11/22/2024 11:08	6.805	0.874	12.780	5.1767	0.38201	0.00222	**0.00194**	**0.01554**	NO
11/29/2024 13:03	13.885	7.079	18.255	5.1766	0.38007	-0.00027	**-0.00194**	**-0.00192**	YES
12/6/2024 14:43	20.954	7.070	22.426	5.1765	0.37813	-0.00027	**-0.00194**	**-0.00192**	YES
12/13/2024 9:52	27.752	6.798	25.808	5.1758	0.36455	-0.00200	**-0.01357**	**-0.01398**	YES



Heat Release Testing, Antero 800



Specimen	Peak RHR (kW/m²)	Peak Time (mm:ss)	THR at 2 minutes (kW*min/m²)	Thermopile Baseline (mV)
1	56.07	04:25	0.04	28.95
2	50.62	04:47	0.41	29.61
3	49.52	03:52	0.84	29.27
4	48.25	03:01	0.16	29.53
Average	51.12	04:01	0.36	29.34

Negative heat release values suppressed : Yes

Specimen 1 Notes

NTPAM8000Q1-STR-800NA-AIR-A-M2-XZ-HRP-RTA-2
Sample started melting and then caught on fire

Specimen 2 Notes

NTPAM8000Q1-STR-800NA-AIR-A-M2-XY-HRP-RTA-2
Sample started to melt and caught on fire

Specimen 3 Notes

NTPAM8000Q1-STR-800NA-AIR-A-M2-ZX-HRP-RTA-2
Sample started to melt and then caught on fire

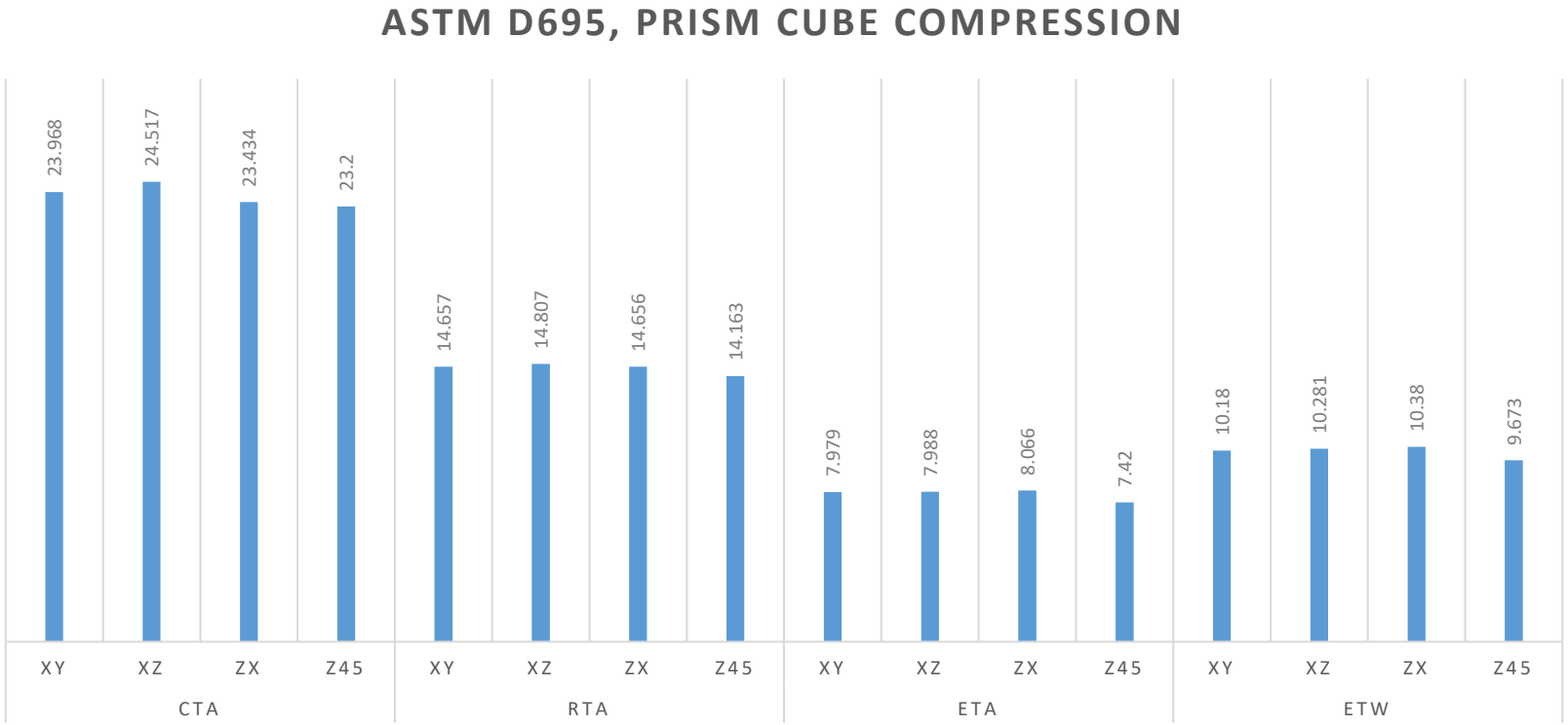
Specimen 4 Notes

NTPAM8000Q1-STR-800NA-AIR-A-M2-Z45-HRP-RTA-2
Sample started to melt and then caught on fire

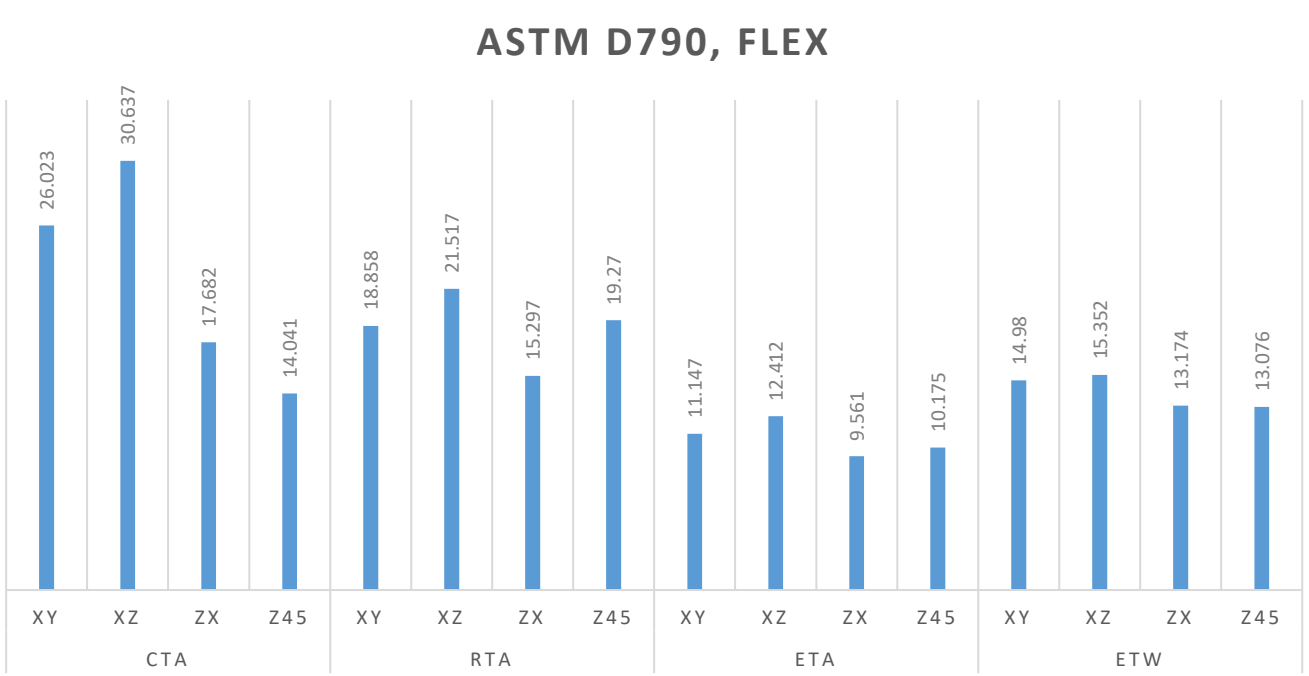
Antero 800 Mechanical Testing Data, UDRI

Strength (Ksi)

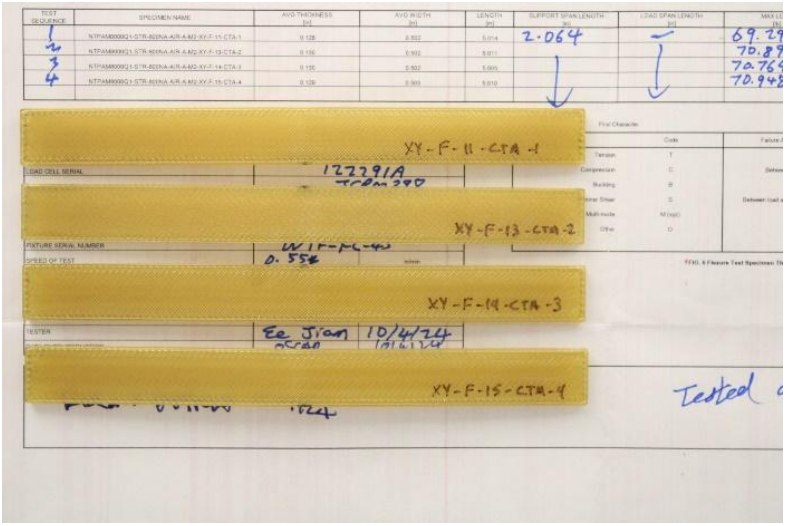
Antero 800 Mechanical Testing Data, UDRI

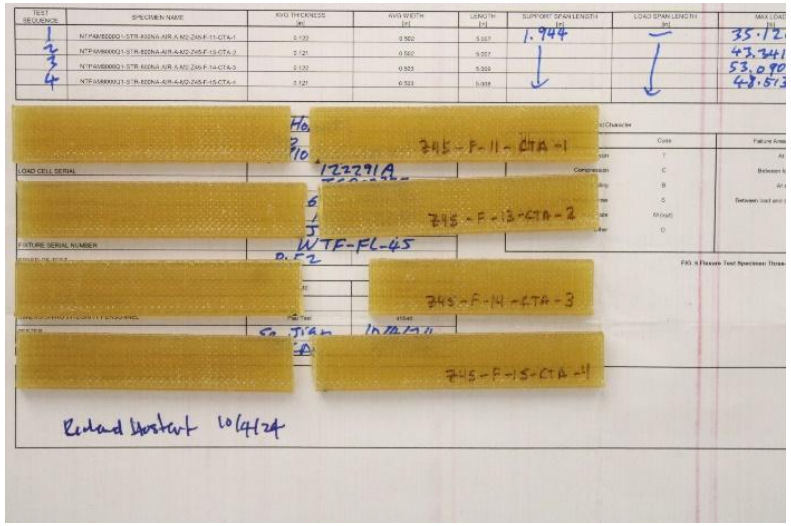


Antero 800 Mechanical Testing Data, UDRI

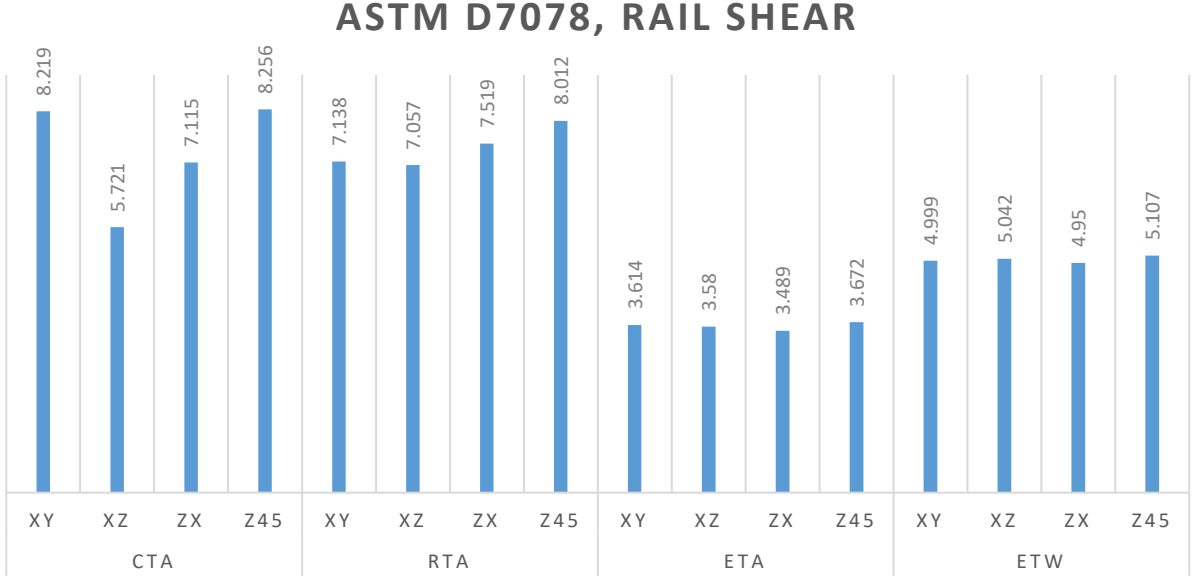


Strength (Ksi)

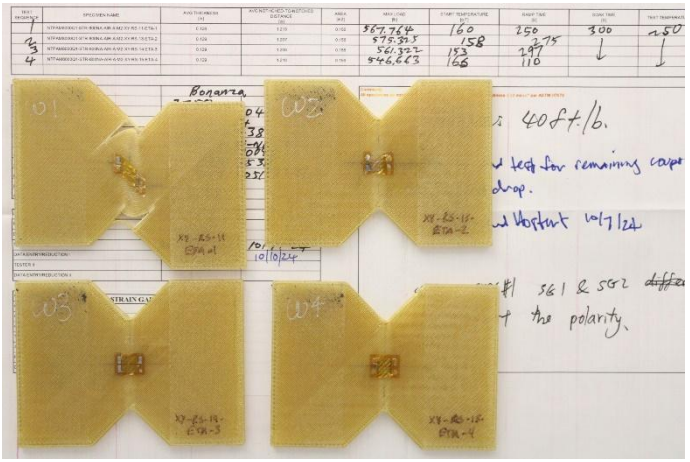




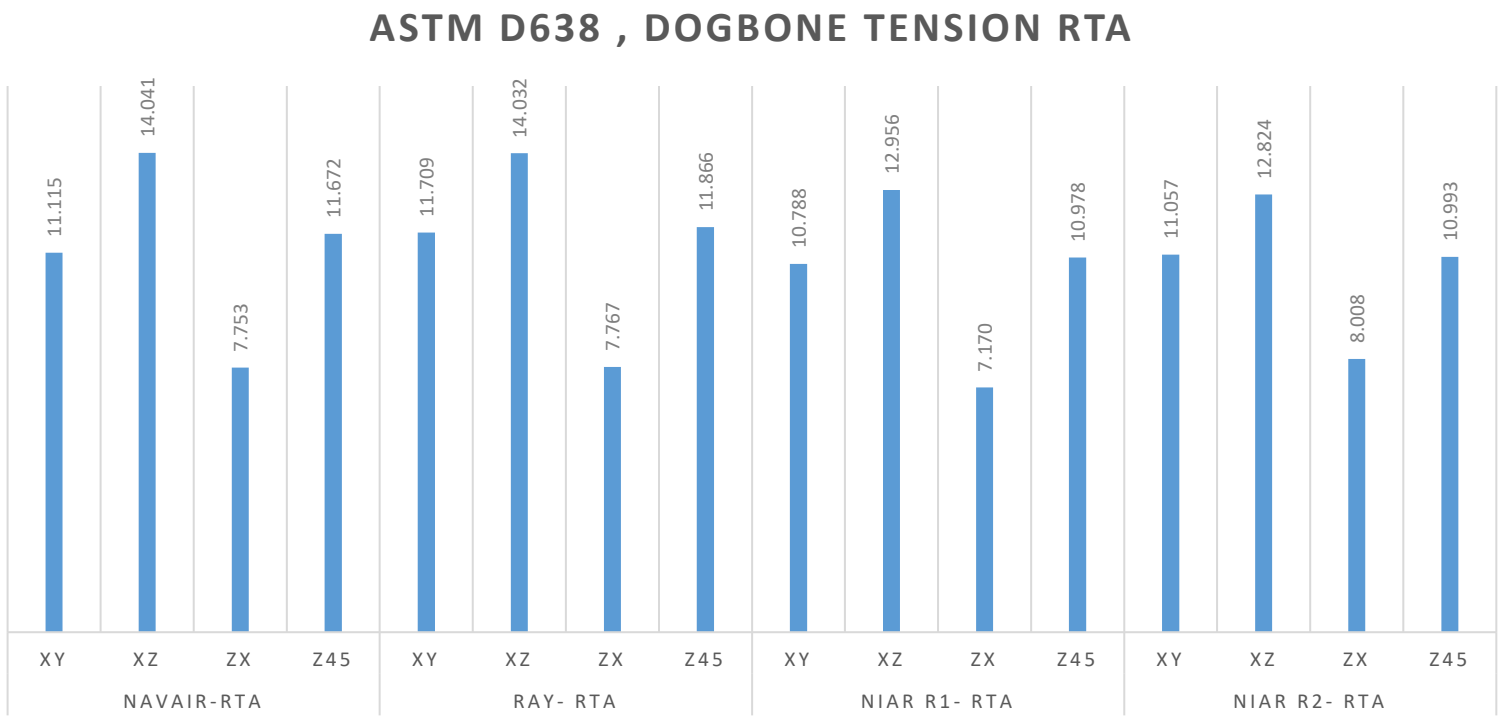
Antero 800 Mechanical Testing Data, UDRI

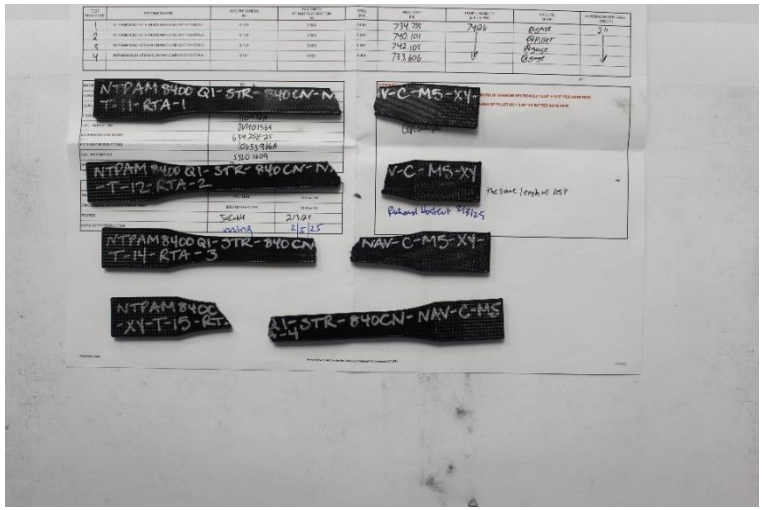


Strength (Ksi)



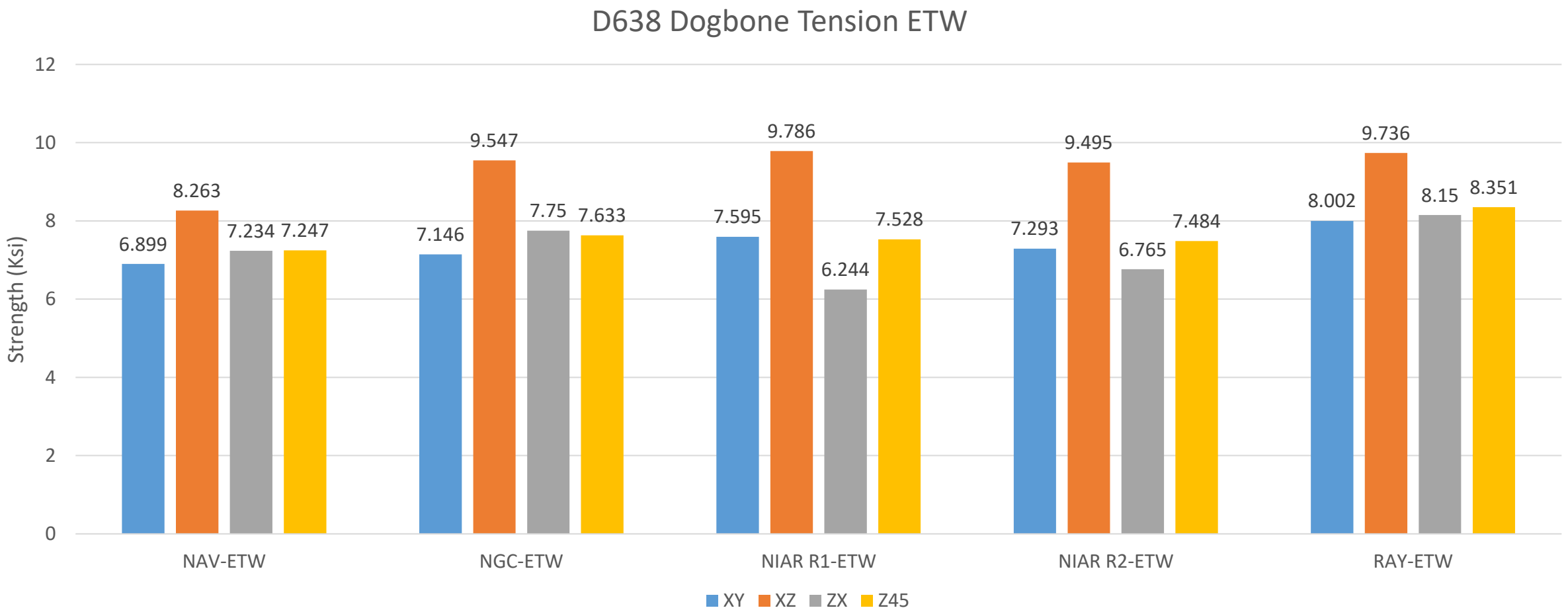
Antero 840 Mechanical Testing Data, D638 RTA



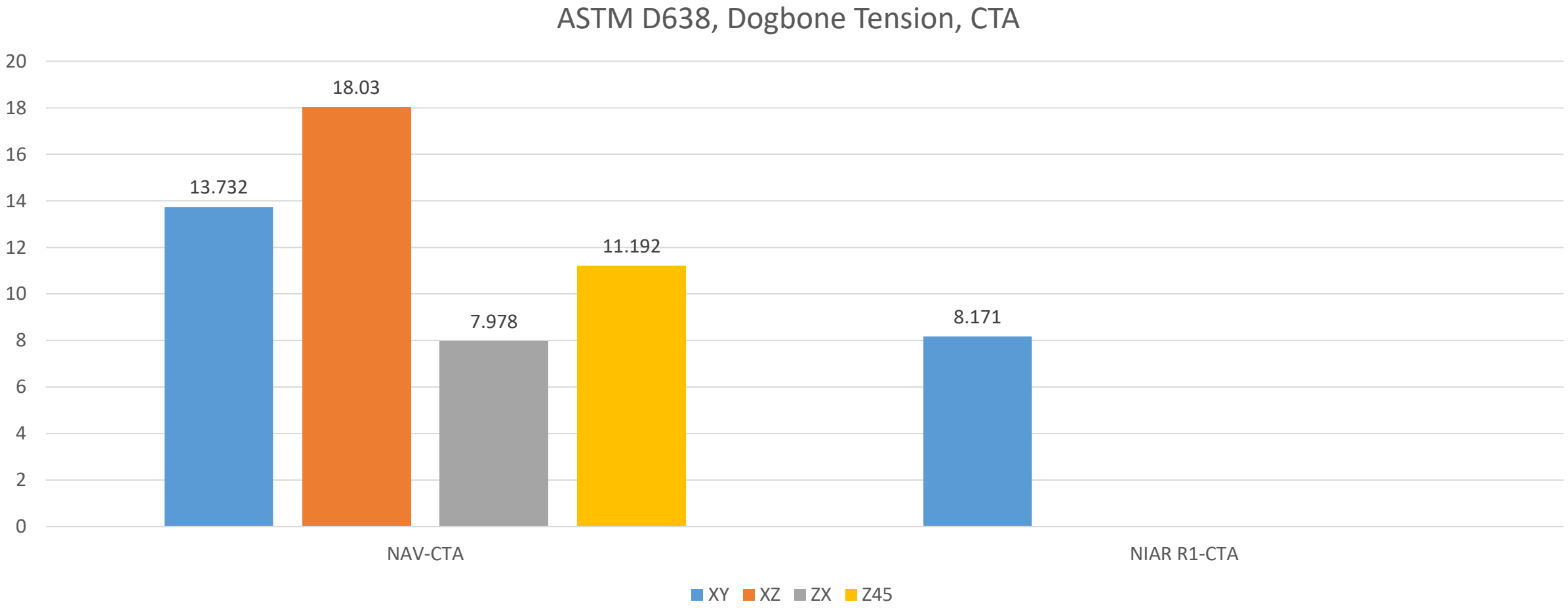


Strength (Ksi)

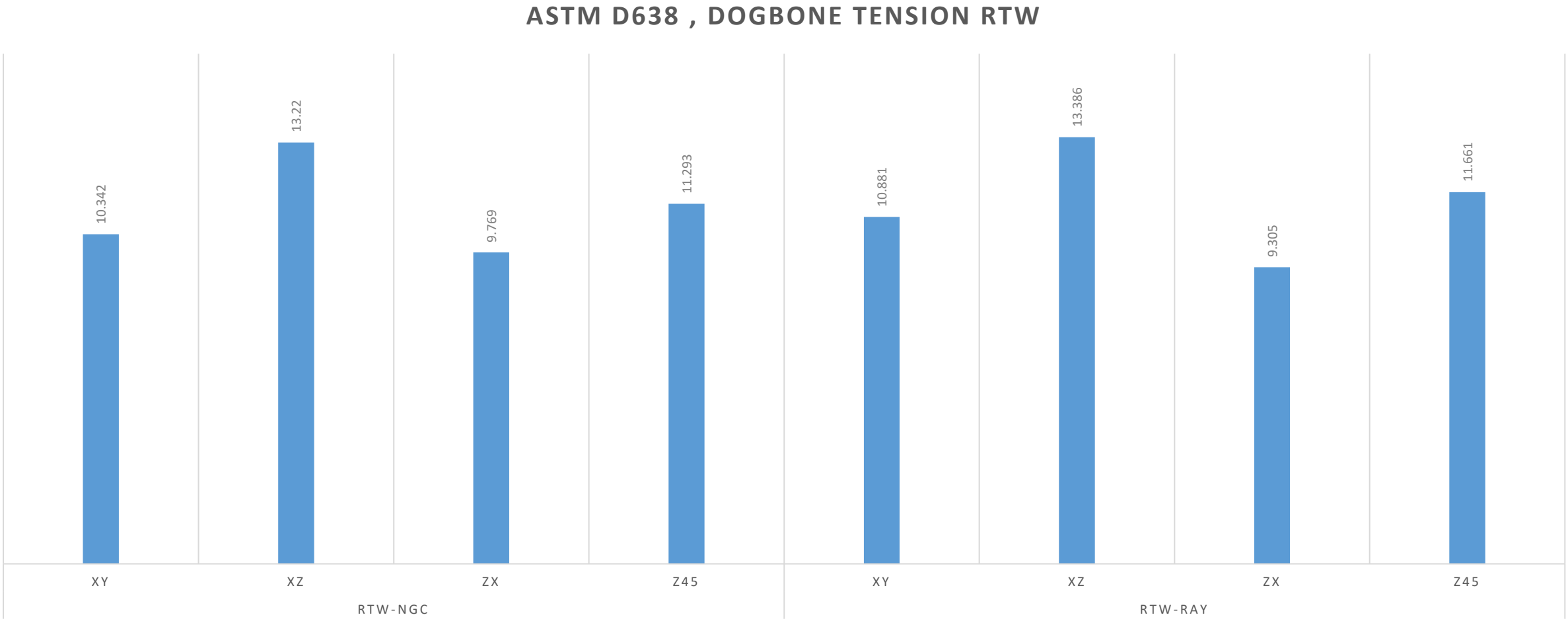
Antero 840 Mechanical Testing Data, D638 ETW



Antero 840 Mechanical Testing Data, D638 CTA

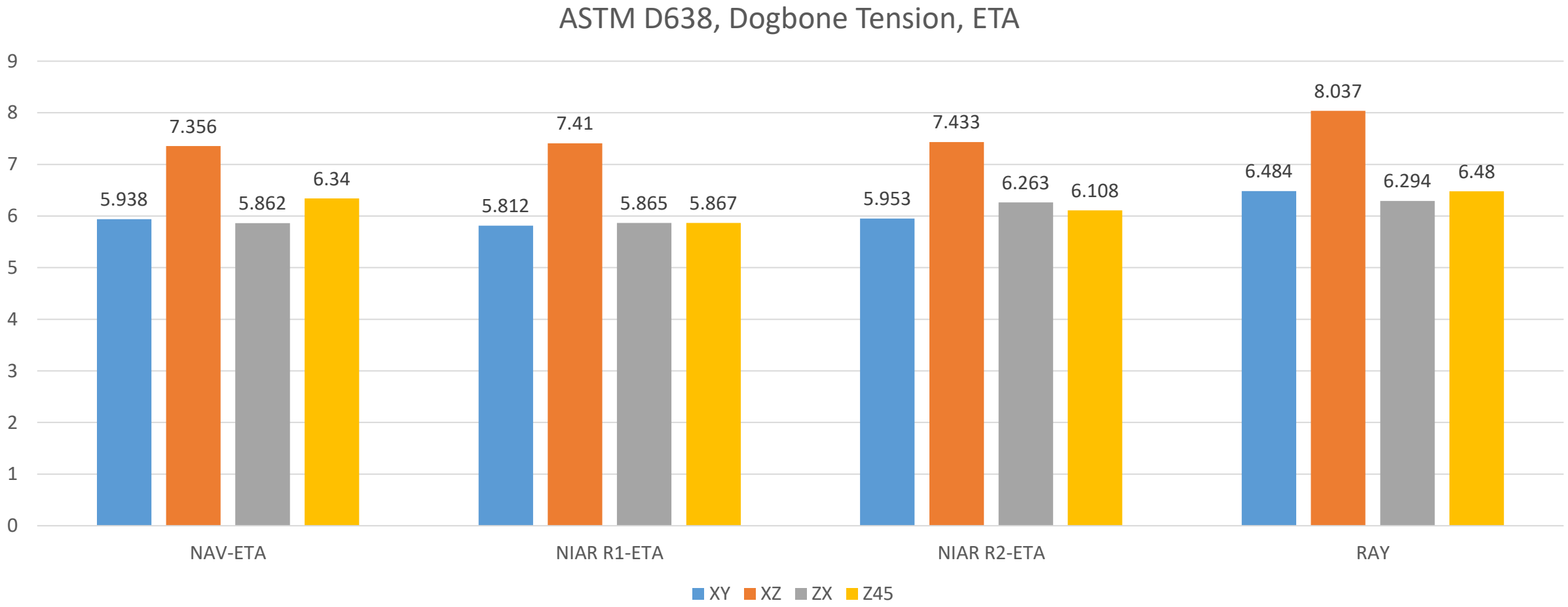


Antero 840 Mechanical Test Data, D638 RTW

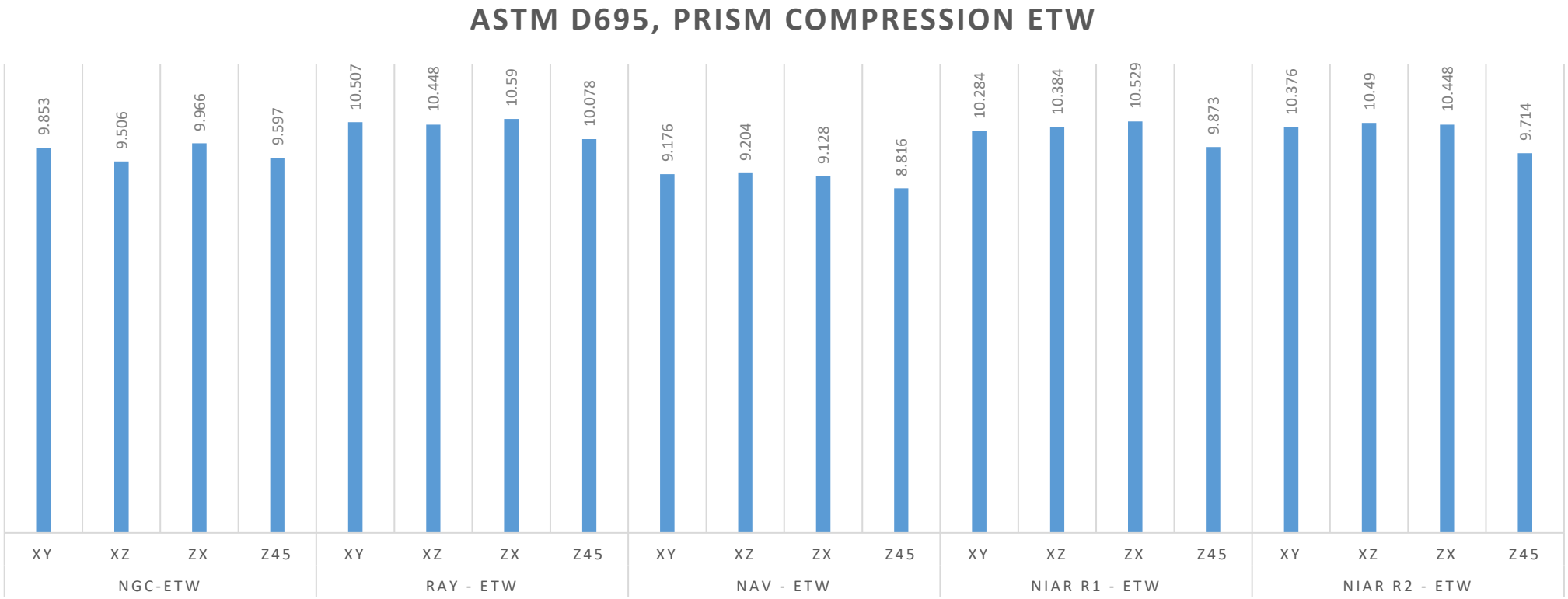


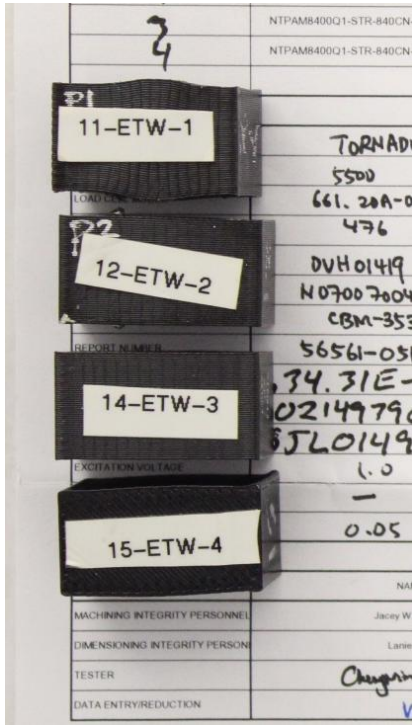
Strength (Ksi)

Antero 840 Mechanical Testing Data, D638 ETA



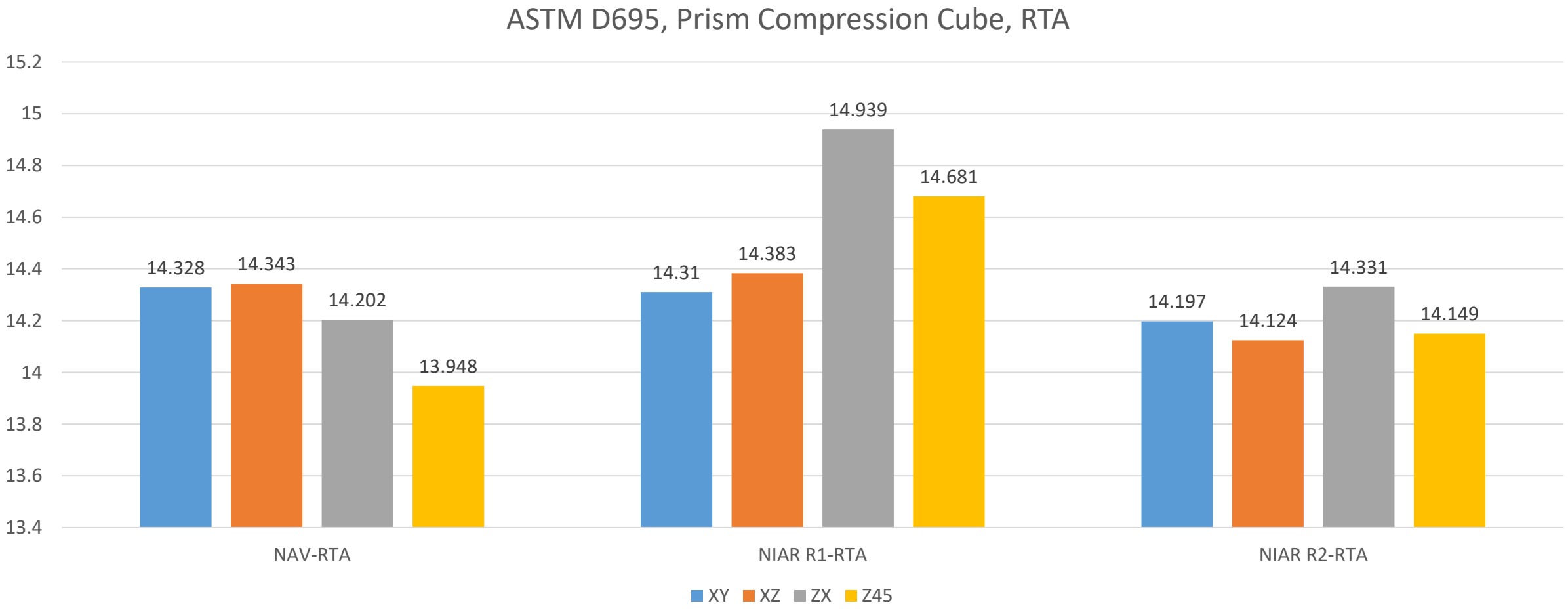
Antero 840 Mechanical Testing Data, D695 ETW



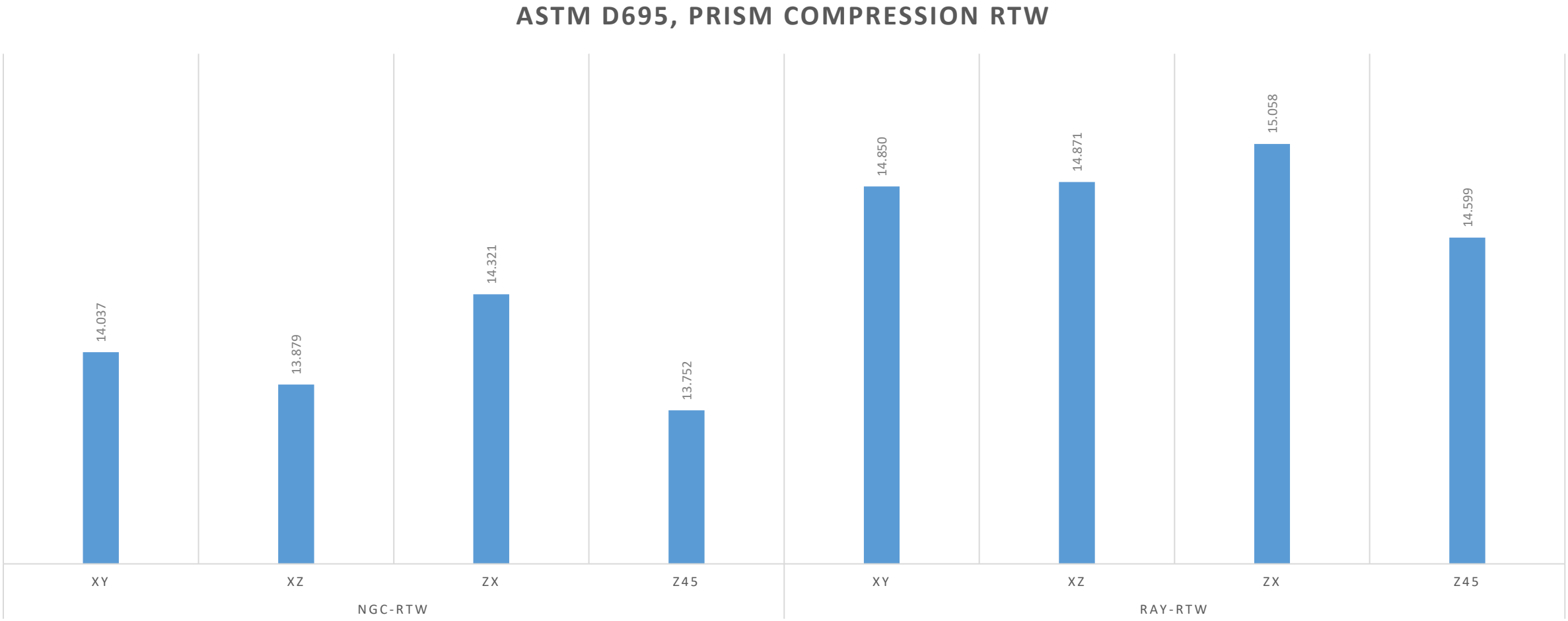


Strength (Ksi)

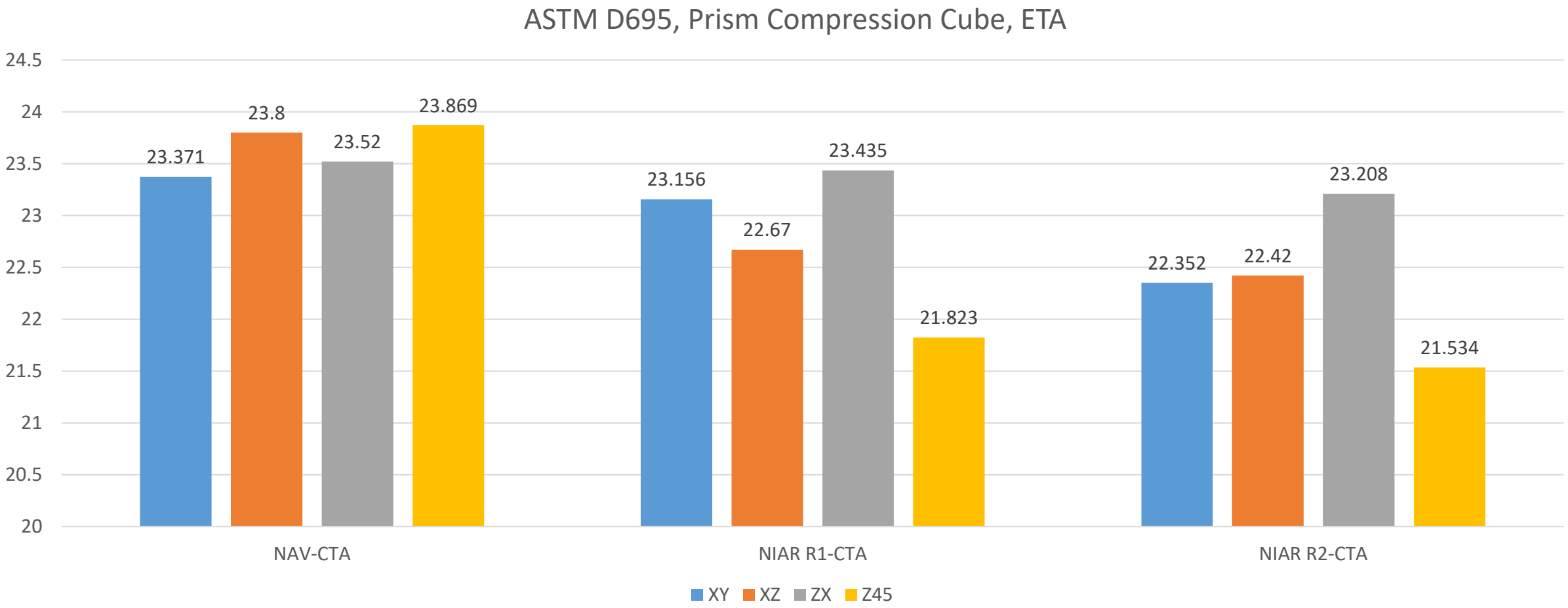
Antero 840 Mechanical Testing Data, D695 RTA



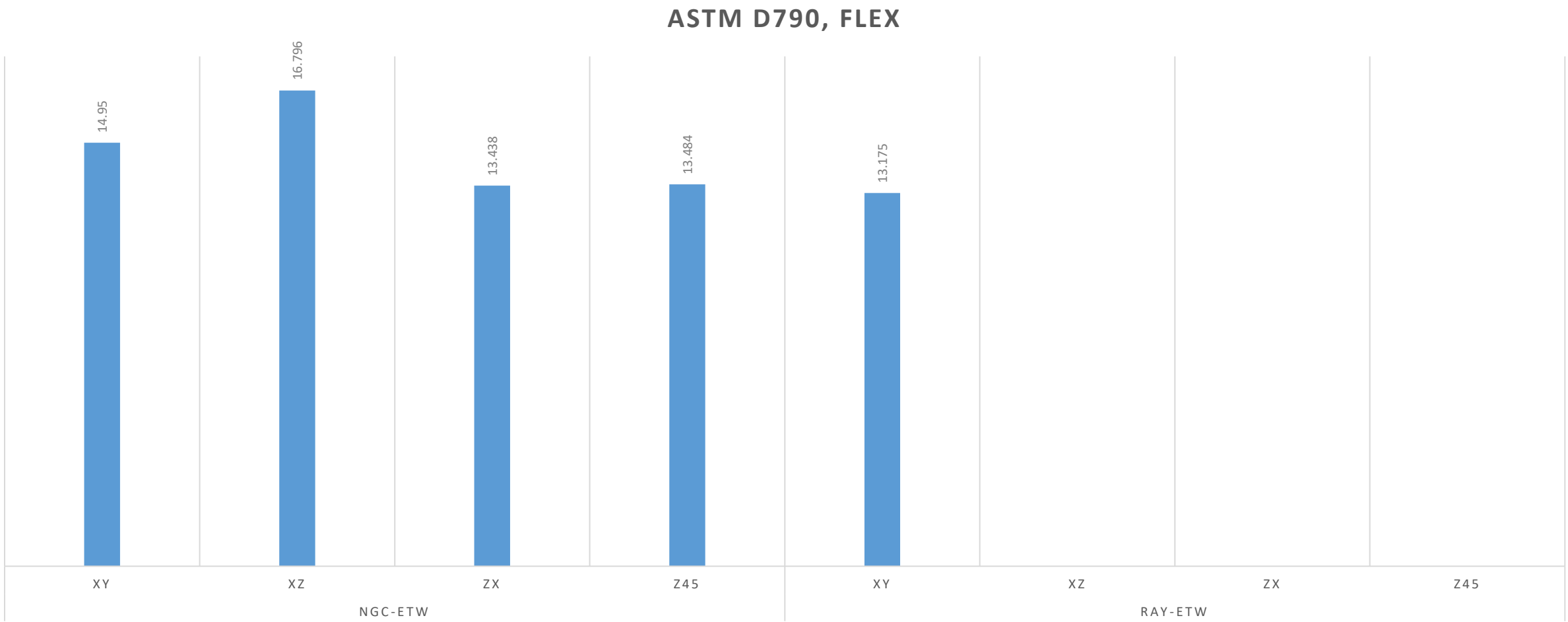
Antero 840 Mechanical Testing Data, D695 RTW



Antero 840 Mechanical Testing Data, D695 CTA

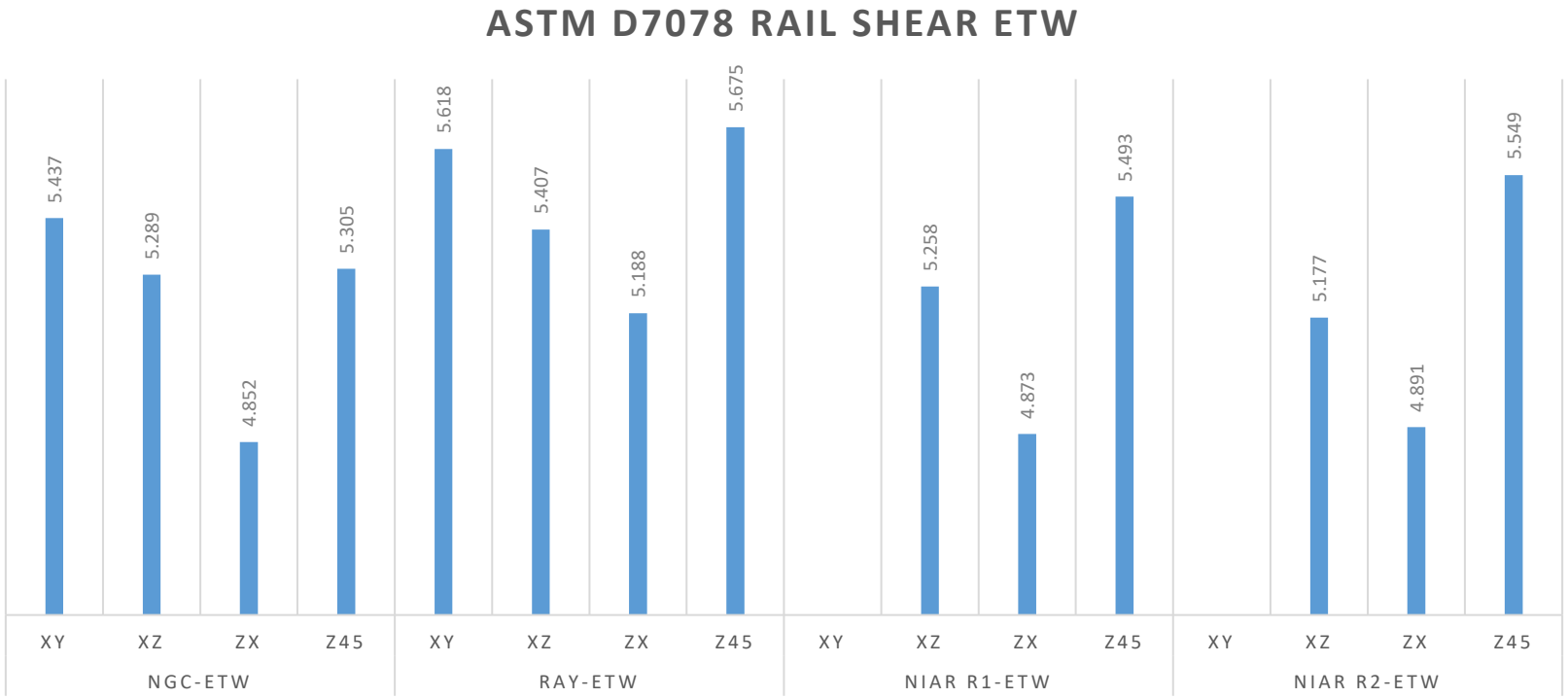


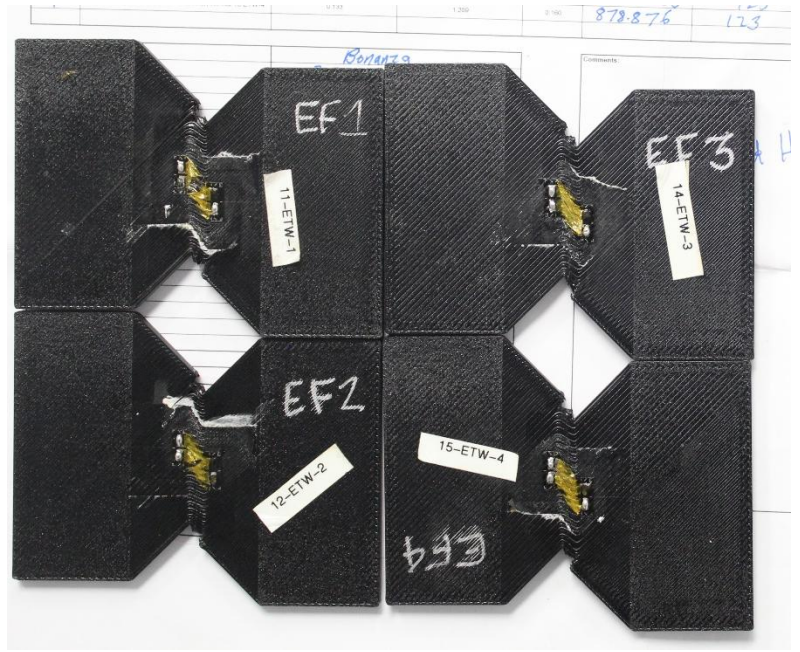
Antero 840 Mechanical Testing Data, NGC-RAY



Strength (Ksi)

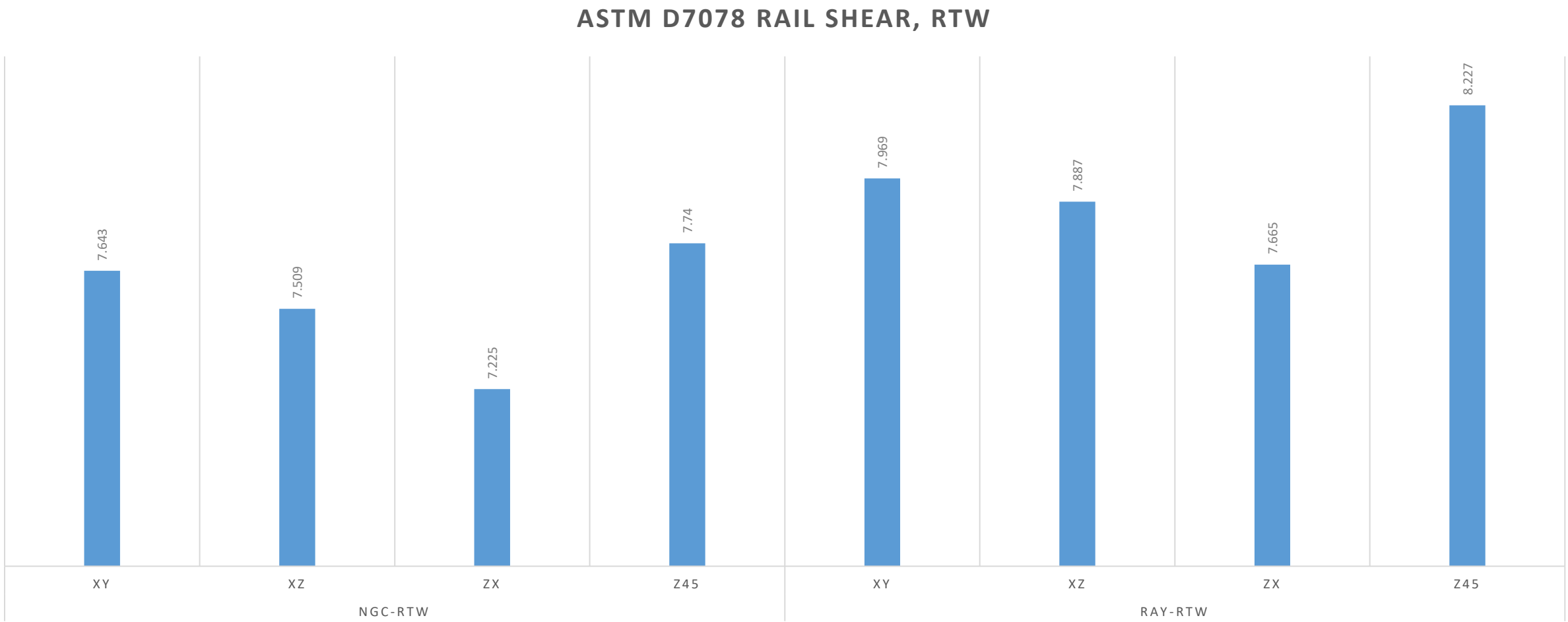
Antero 840 Mechanical Testing Data, Rail Shear ETW



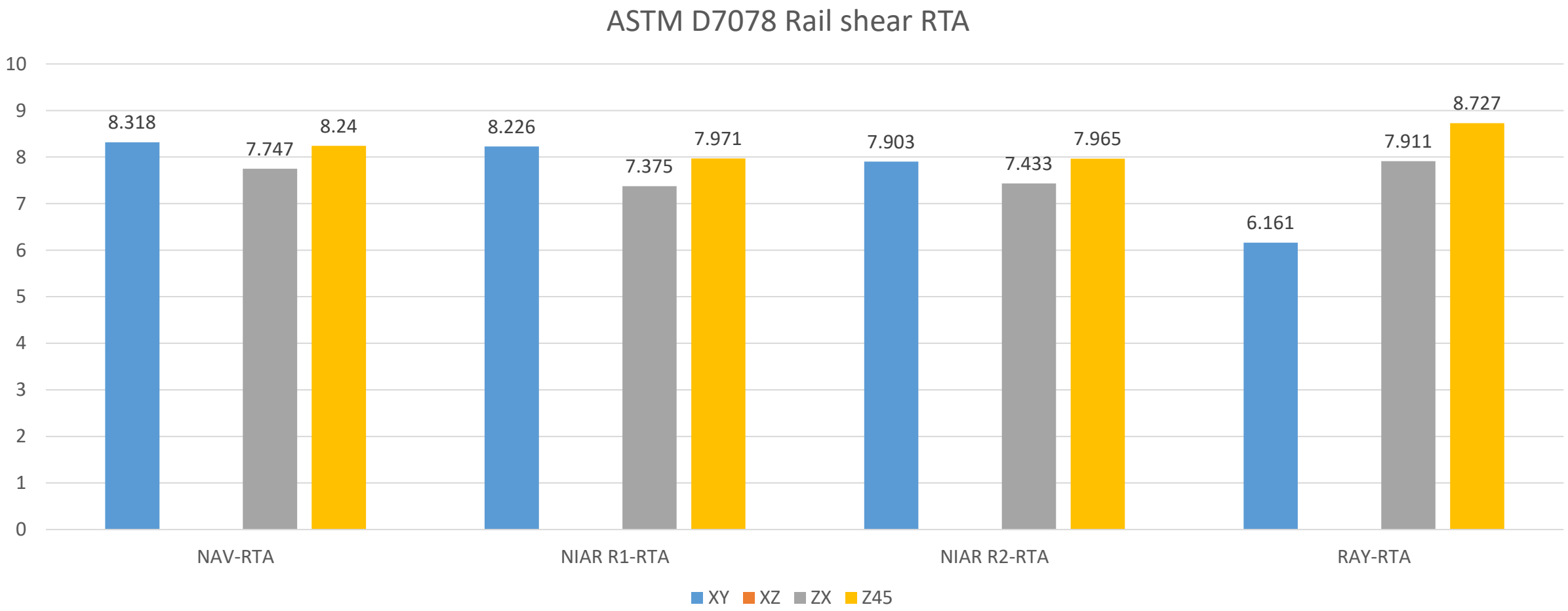


Strength (Ksi)

Antero 840 Mechanical Testing Data, Rail Shear RTW



Strength (Ksi)


ASTM D7078 Rail shear RTA
10
9
8
7
6
5
4
3
2
1
0
8.318
7.747
8.24
8.226
7.375
7.971
7.903
7.433
7.965
6.161
7.911
8.727
NAV-RTA
NIAR R1-RTA
NIAR R2-RTA
RAY-RTA
XY
XZ
ZX
Z45

All coupons at XZ print direction yielded a bad failure mode, thus the data were not reported. This was consistently observed across all batches.

Antero 840 Mechanical Testing Data, RAYTHEON

SPECIMEN NAME	AVG THICKNESS [in]	AVG WIDTH [in]	AREA [in^2]	HOLE DIAMETER [in]	INITIAL LOAD OFFSET [lb]	MAX LOAD [lb]	OPEN HOLE TENSILE STRENGTH [ksi]	TEST TEMPERATURE [^oF]	FAILURE MODE
NTPAM8400Q1-STR-840CN-RAY-A-M2-XY-OHT-11-ETW-1	0.131	1.503	0.197	0.251	0.0	1184.855	6.026	180F	M(A,L)GM
NTPAM8400Q1-STR-840CN-RAY-A-M2-XY-OHT-12-ETW-2	0.131	1.503	0.197	0.251	0.0	1142.301	5.797	180F	M(A,L)GM
NTPAM8400Q1-STR-840CN-RAY-A-M2-XY-OHT-14-ETW-3	0.131	1.501	0.197	0.252	0.0	1130.405	5.739	180F	M(A,L)GM
NTPAM8400Q1-STR-840CN-RAY-A-M2-XY-OHT-15-ETW-4	0.131	1.502	0.197	0.251	0.0	1134.645	5.766	180F	M(A,L)GM

	AVERAGE	5.832
	STANDARD DEVIATION	0.131
	COEFFICIENT OF VARIATION [%]	2.253

Strength (Ksi)

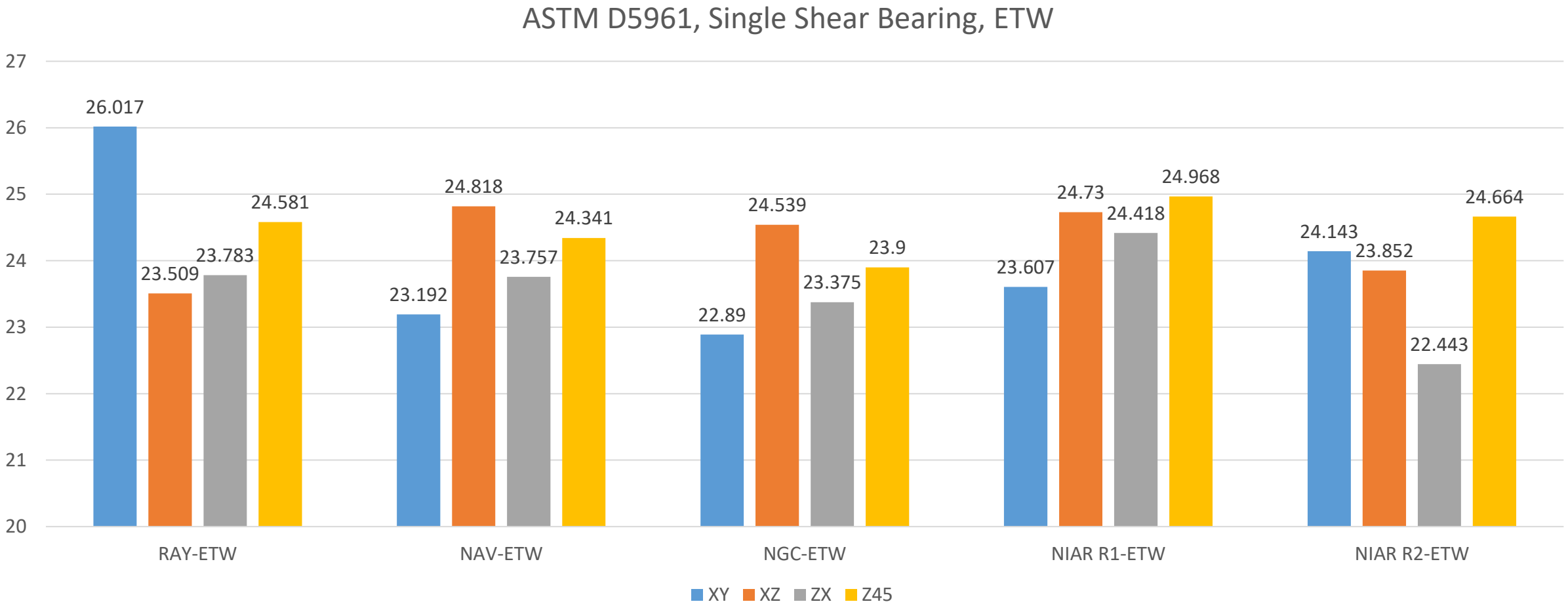
Antero 840 Mechanical Testing Data, RAYTHEON

SPECIMEN NAME	AVG THICKNESS [in]	AVG WIDTH [in]	AREA [in^2]	HOLE DIAMETER [in]	OVERALL LENGTH [in]	LOAD PER HOLE FACTOR	INITIAL LOAD OFFSET [lb]	ULTIMATE LOAD [lb]	ULTIMATE BEARING STRENGTH [ksi]	2% OFFSET BEARING STRENGTH [ksi]	INITIAL PEAK BEARING STRENGTH [ksi]	BEARING STIFFNESS [Msi]	TEST TEMPERATURE [^oF]	PREVAILING TORQUE [in-lbs]	FAILURE MODE
NTPAM8400Q1-STR-840CN-RAY-A-M2-XY-SSB-11-ETW-1	0.203	1.501	0.304	0.251	5.503	1.0	0.0	1342.251	26.439	20.359		0.208	180F	12	B1I
NTPAM8400Q1-STR-840CN-RAY-A-M2-XY-SSB-12-ETW-2	0.203	1.501	0.305	0.251	5.504	1.0	0.0	1312.537	25.750	20.873		0.186	180F	14	B1I
NTPAM8400Q1-STR-840CN-RAY-A-M2-XY-SSB-14-ETW-3	0.203	1.500	0.305	0.251	5.505	1.0	0.0	1355.312	26.553	22.404		0.217	180F	10	B1I
NTPAM8400Q1-STR-840CN-RAY-A-M2-XY-SSB-15-ETW-4	0.203	1.501	0.305	0.253	5.504	1.0	0.0	1303.654	25.325	20.738		0.208	180F	11	B1I

	AVERAGE	26.017	21.094	#DIV/0!	0.205
	STANDARD DEVIATION	0.582	0.900	#DIV/0!	0.013
	COEFFICIENT OF VARIATION [%]	2.237	4.269	#DIV/0!	6.481

Strength (Ksi)

Antero 840 Mechanical Testing Data, SSB



Antero 840 Mechanical Testing Data, RAYTHEON

SPECIMEN NAME	AVG THICKNESS [in]	AVG WIDTH [in]	AREA [in^2]	HOLE DIAMETER [in]	INITIAL LOAD OFFSET [lb]	MAX LOAD [lb]	FILLED-HOLE TENSILE STRENGTH [ksi]	PREVAILING TORQUE [in-lbs]	TEST TEMPERATURE [^oF]	FAILURE MODE
NTPAM8400Q1-STR-840CN-RAY-A-M2-XY-FHT-11-ETW-1	0.132	1.500	0.198	0.251	0.0	1204.425	6.091	13	180F	M(A,L)GM
NTPAM8400Q1-STR-840CN-RAY-A-M2-XY-FHT-12-ETW-2	0.131	1.502	0.197	0.251	0.0	1175.168	5.951	17	180F	M(A,L)GM
NTPAM8400Q1-STR-840CN-RAY-A-M2-XY-FHT-14-ETW-3	0.133	1.501	0.199	0.254	0.0	1167.177	5.864	20	180F	M(A,L)GM
NTPAM8400Q1-STR-840CN-RAY-A-M2-XY-FHT-15-ETW-4	0.132	1.503	0.198	0.251	0.0	1165.200	5.891	23	180F	M(A,L)GM

AVERAGE	5.949
STANDARD DEVIATION	0.101
COEFFICIENT OF VARIATION [%]	1.706

Strength (Ksi)

Thank you

Questions?