SOLUTIONS FOR THE BUILT WORLD

Arecibo Observatory

Auxiliary Main Cable Socket Failure Investigation

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WJE ENGINEERS ARCHITECTS MATERIALS SCIENTISTS

Wiss, Janney, Elstner Associates, Inc.

2023 Structural Engineering Webinar Series

Jonathan C. McGormley, P.E., S.E.

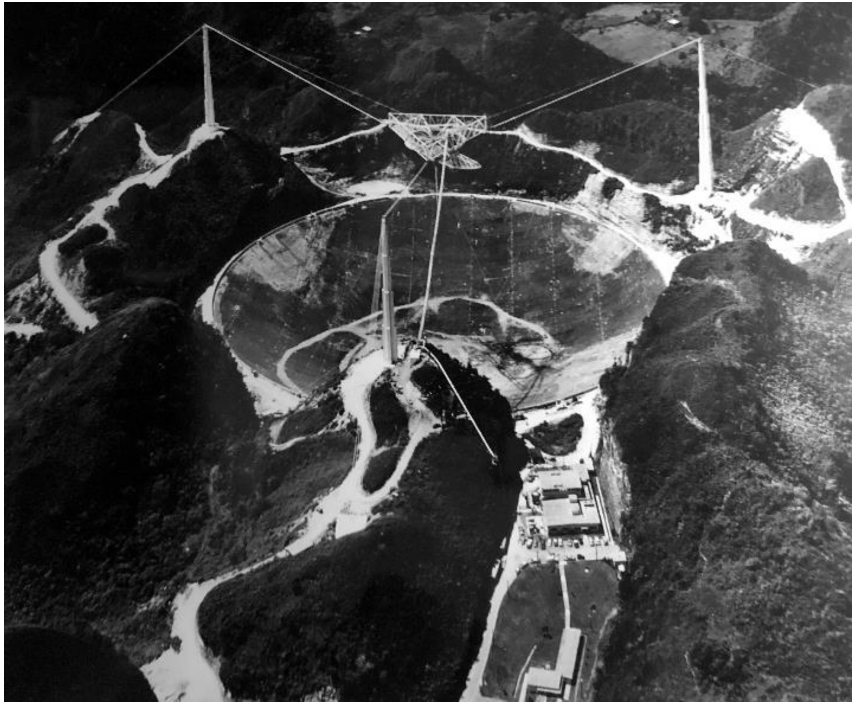
Background Information

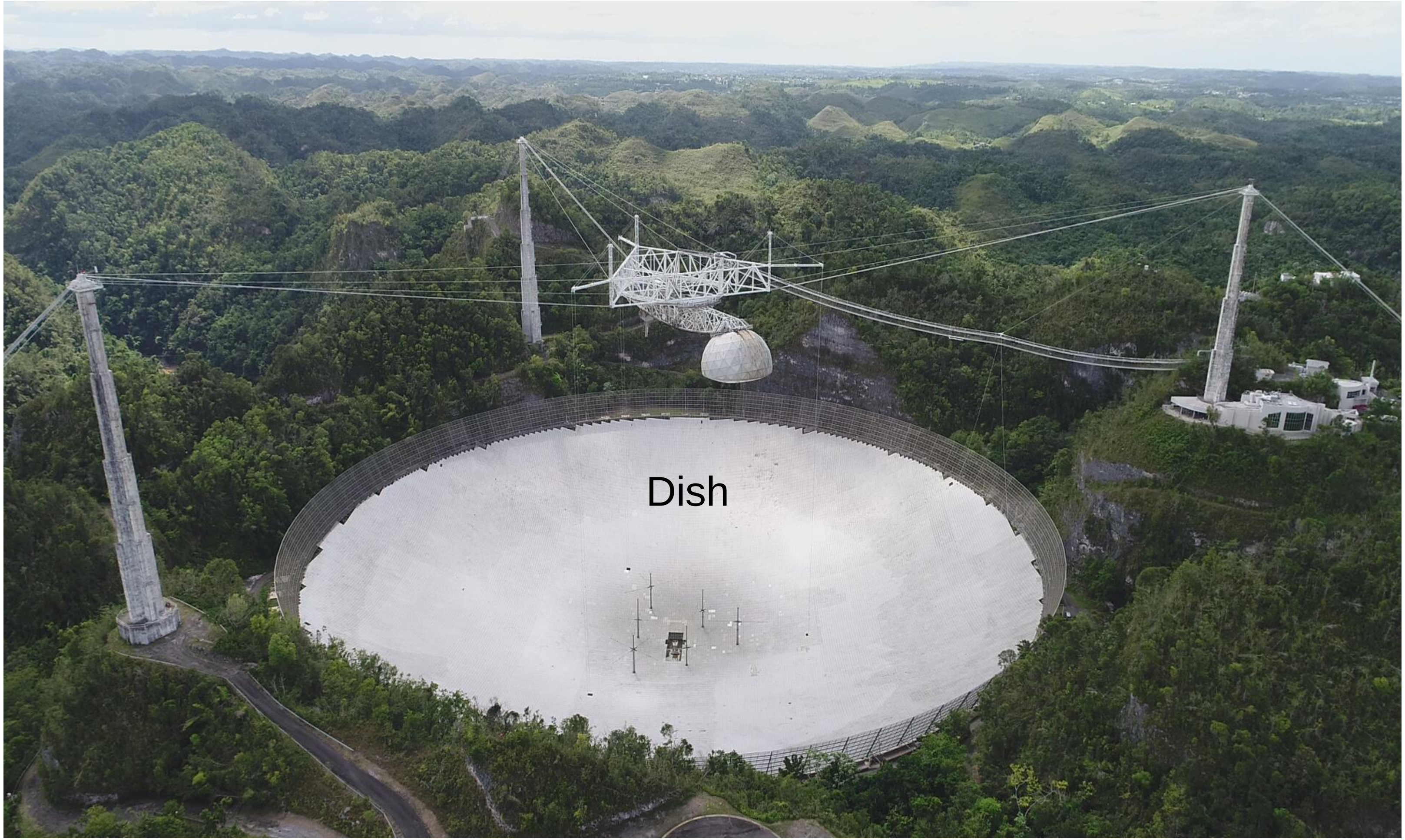
- Original Design
- New Gregorian Dome Upgrade Modifications
- Auxiliary Mains
- Sockets


Arecibo Observatory/NASA/NSF
3200 Phaethon
17 Dec 2017 UT

Photo from Arecibo Observatory

Arecibo Observatory





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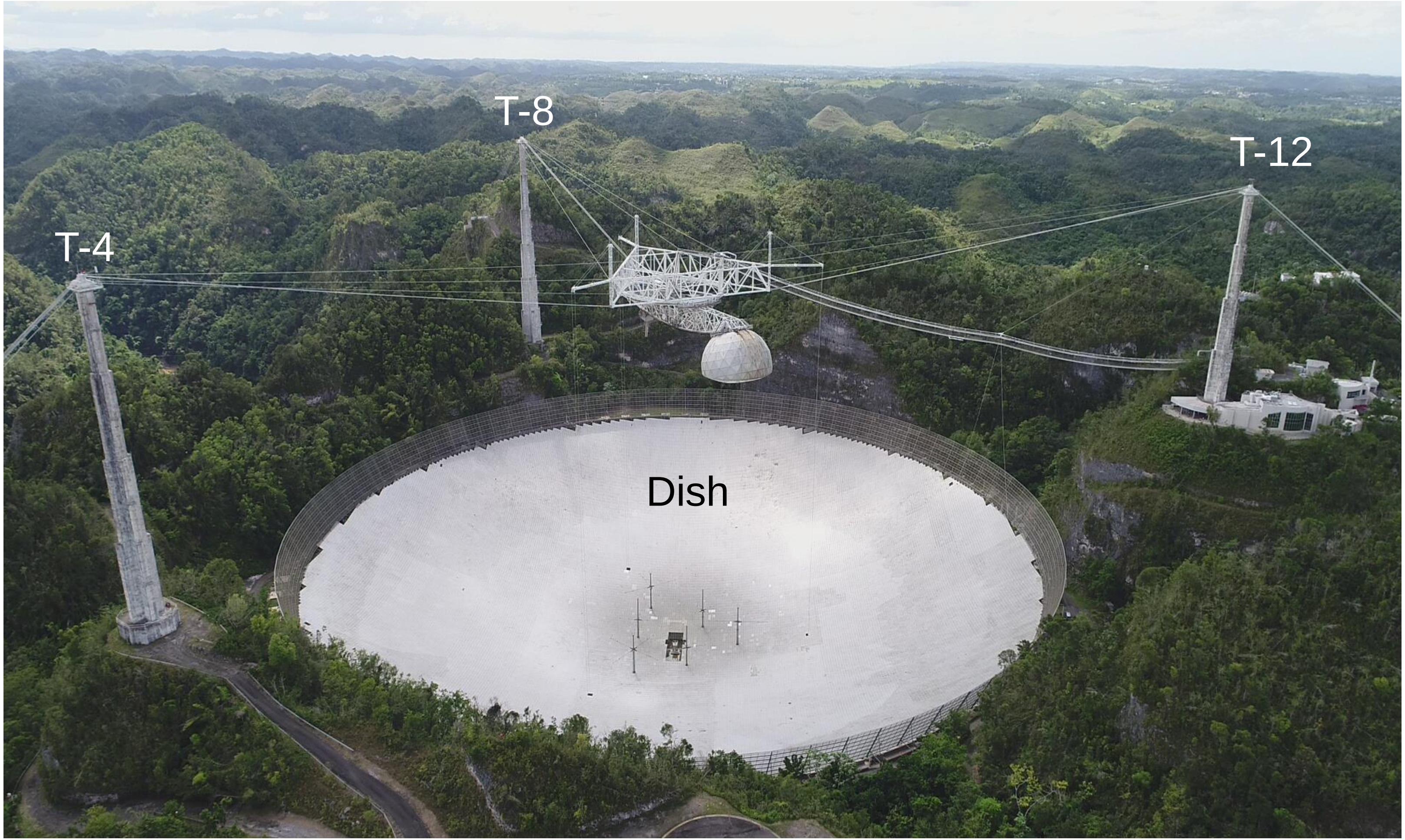

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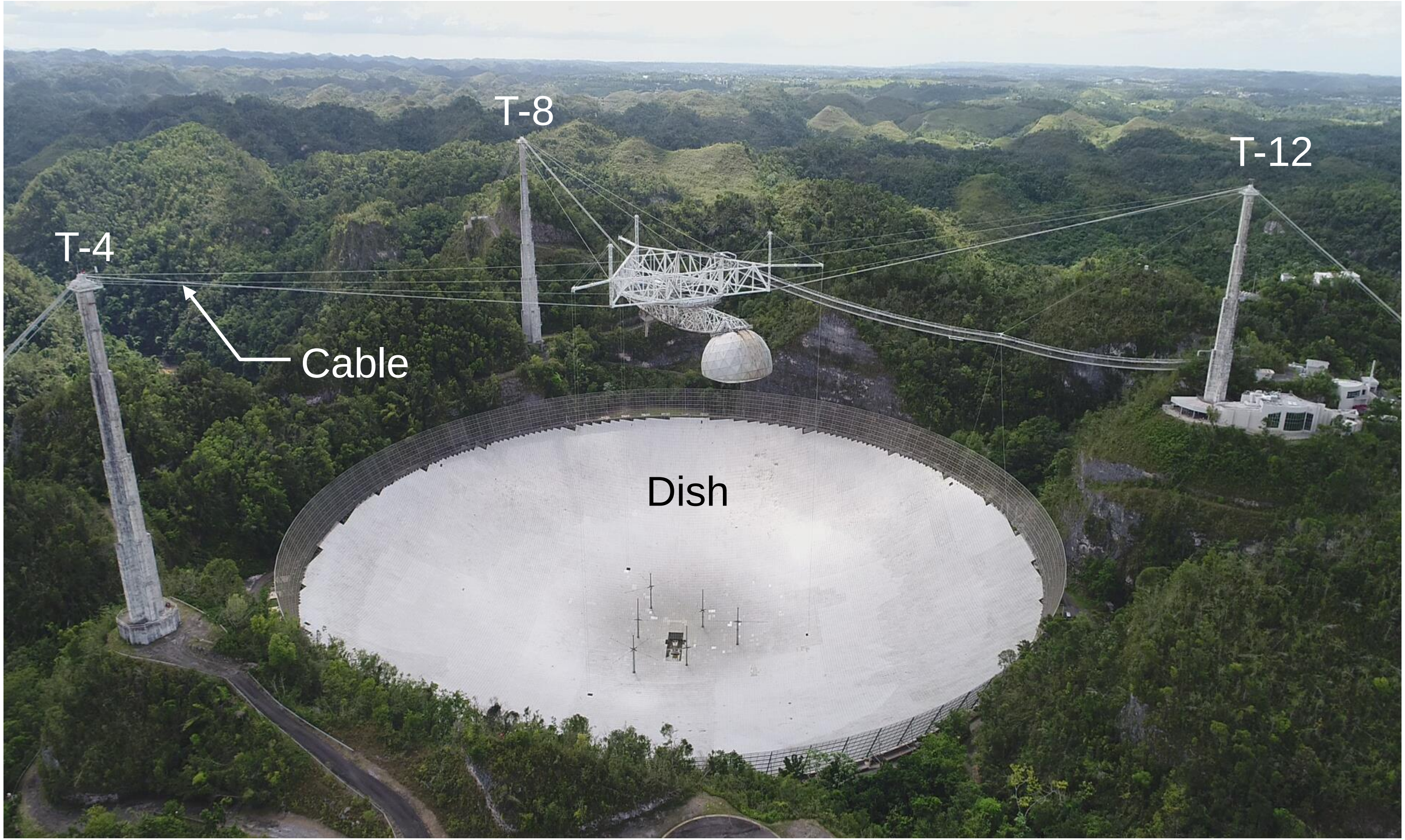

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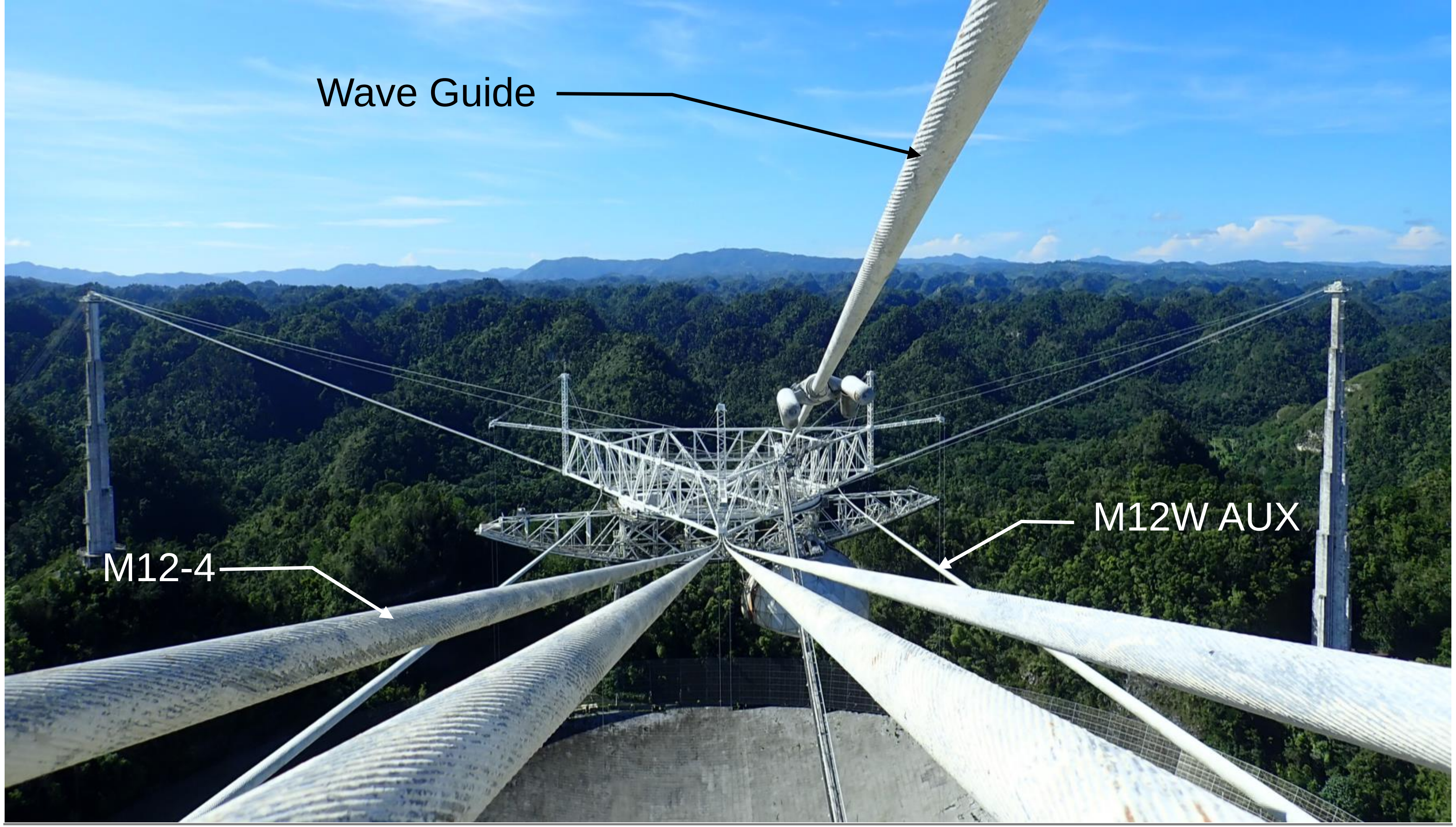
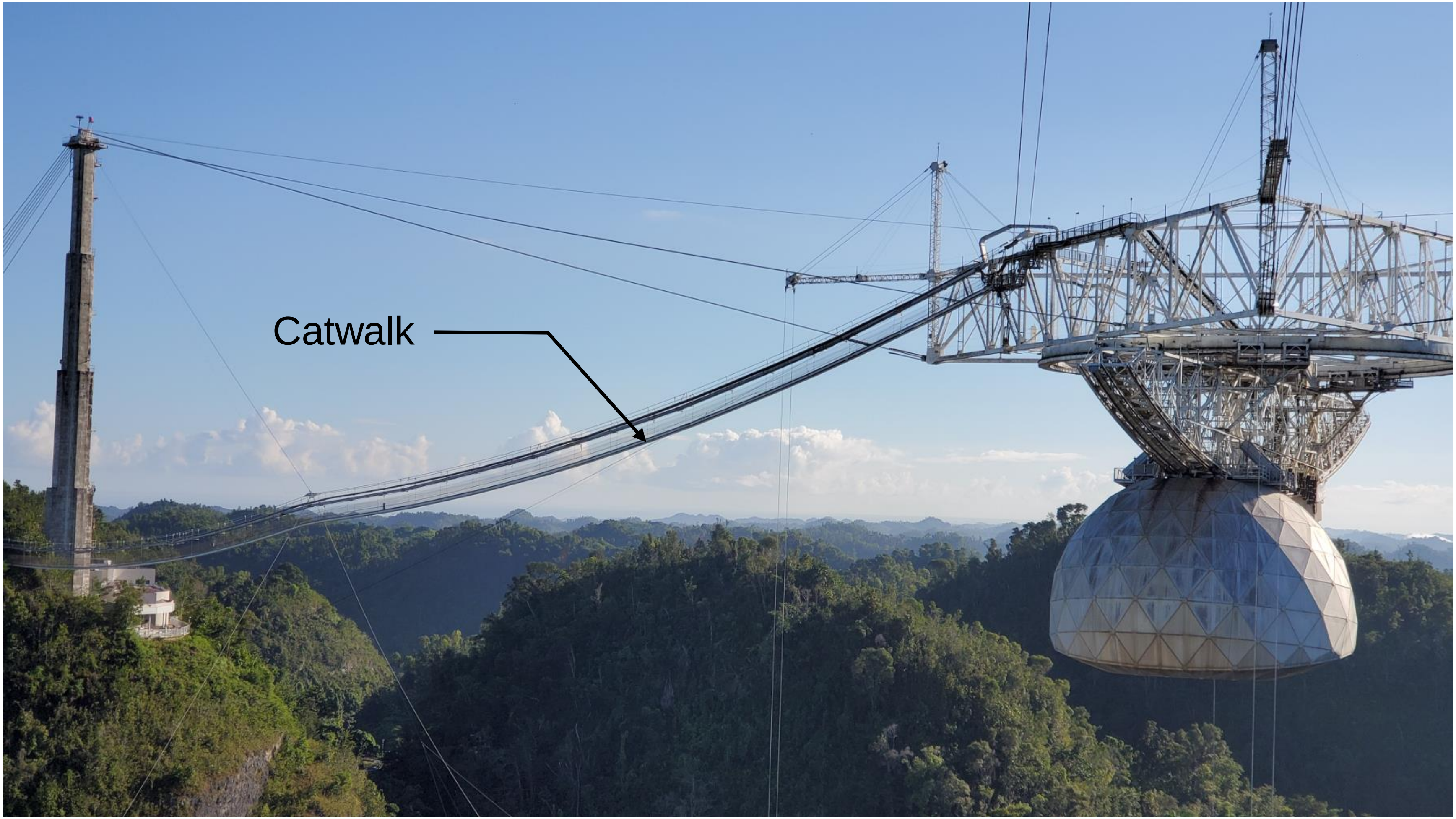

Wave Guide
M12W AUX
M12-4

Photo from Arecibo Observatory


Catwalk

Southwest

BRIDGE & STRUCTURES INC

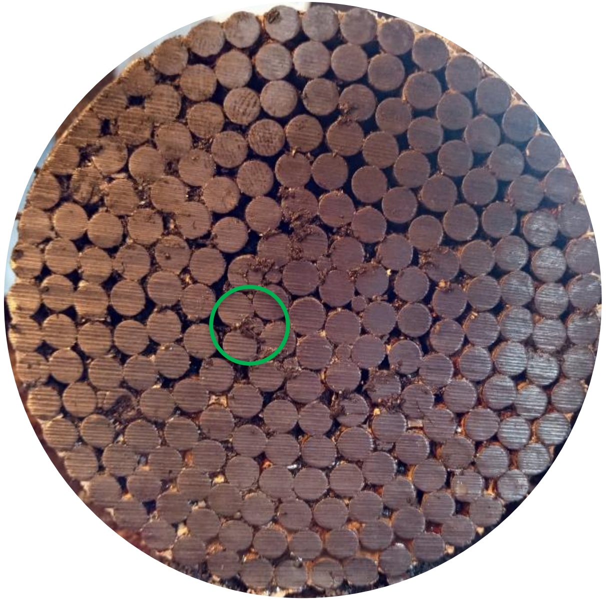
Galvanized Structural Strand

Strand Diam In.	Breaking Strength in Tons of 2,000 Lb: Class "A" Coating Throughout — Standard Grade	Class "A" Coating Throughout — Premium Grade	Class "A" Coating Inner Wires Class "B" Coating Outer Wires	Class "A" Coating Inner Wires Class "C" Coating Outer Wires	Approx Metallic Area Sq In.	Approx Wt/Ft in Lb
½	15.0	....	14.5	14.2	0.15	0.52
9/16	19.0	....	18.4	18.0	0.19	0.66
3	538.	565.	530.	522.	5.40	18.90
3⅛	584.	613.	575.	566.	5.86	20.51
3¼	625.	657.	616.	606.	6.34	22.18
3⅜	673.	707.	663.	653.	6.83	23.92
3½	724.	760.	714.	702.	7.35	25.73
3⅝	768.	807.	757.	745.	7.88	27.60
3¾	822.	863.	810.	797.	8.44	29.53
3⅞	878.	922.	865.	852.	9.01	31.53
4	925.	972.	911.	897.	9.60	33.60
4¼	1040.	1092.	....	....	10.8	37.9
4⅜	1100.	1155.	....	....	11.5	40.2

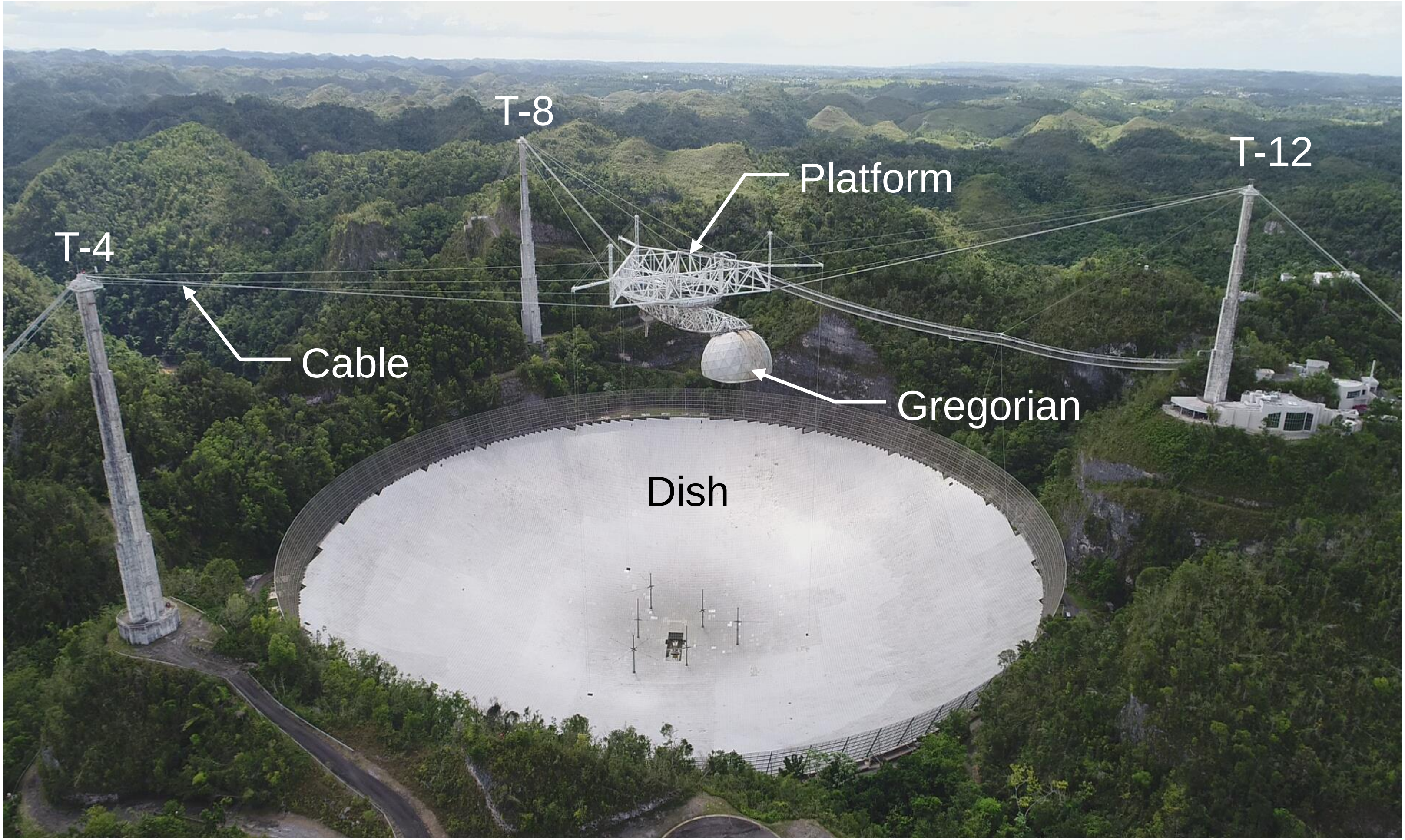
1

Arecibo Cables

Cross section of 3 ¼-inch diam. M4N AUX cable



Cross section of 3 ¼-inch diam. original backstay cable



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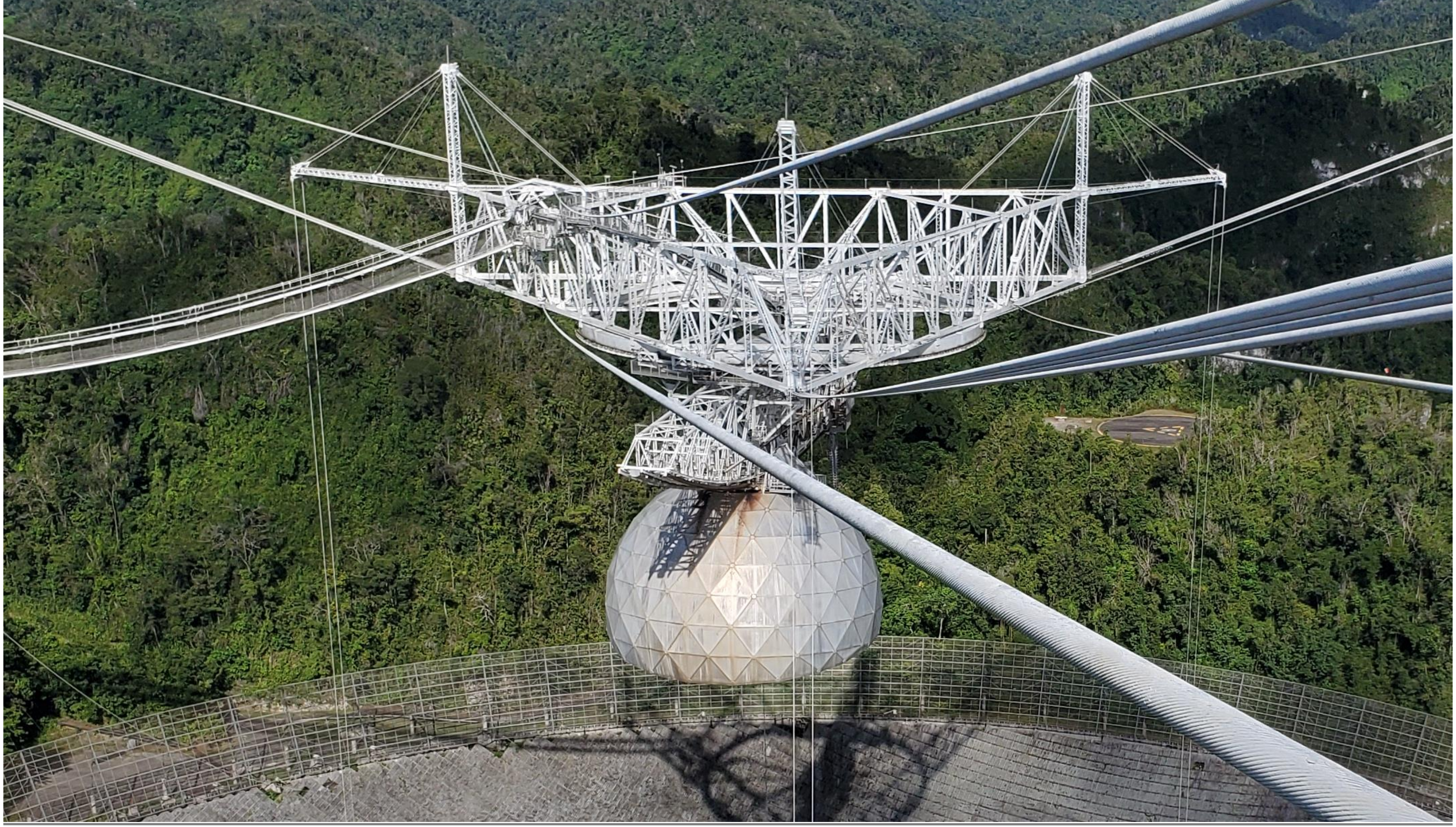

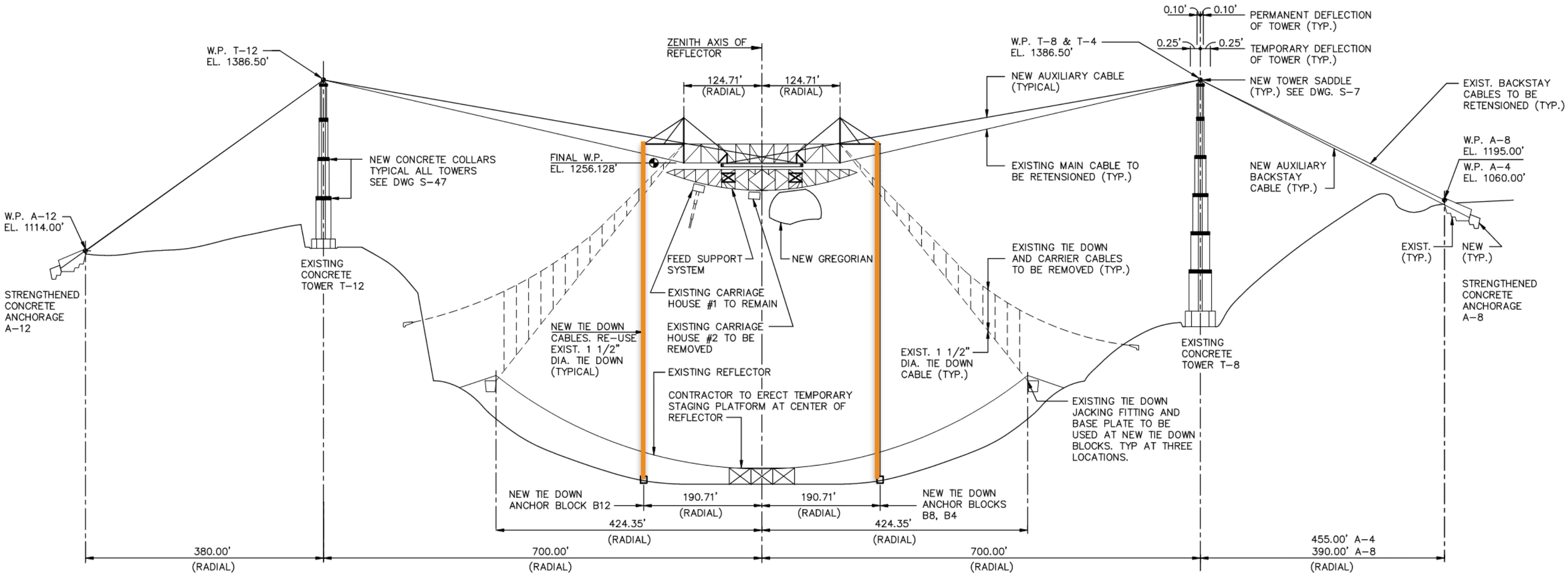

0.10'
0.10'
PERMANENT DEFLECTION OF TOWER (TYP.)
0.25'
0.25'
TEMPORARY DEFLECTION OF TOWER (TYP.)
W.P. T-12 EL. 1386.50'
ZENITH AXIS OF REFLECTOR
W.P. T-8 & T-4 EL. 1386.50'
NEW TOWER SADDLE (TYP.) SEE DWG. S-7
124.71' (RADIAL)
124.71' (RADIAL)
NEW AUXILIARY CABLE (TYPICAL)
EXIST. BACKSTAY CABLES TO BE RETENSIONED (TYP.)
W.P. A-8 EL. 1195.00'
W.P. A-4 EL. 1060.00'
NEW CONCRETE COLLARS TYPICAL ALL TOWERS SEE DWG S-47
FINAL W.P. EL. 1256.128'
EXISTING MAIN CABLE TO BE RETENSIONED (TYP.)
NEW AUXILIARY BACKSTAY CABLE (TYP.)
W.P. A-12 EL. 1114.00'
EXIST. (TYP.)
NEW (TYP.)
FEED SUPPORT SYSTEM
NEW GREGORIAN
EXISTING TIE DOWN AND CARRIER CABLES TO BE REMOVED (TYP.)
EXISTING CONCRETE TOWER T-12
STRENGTHENED CONCRETE ANCHORAGE A-12
EXISTING CARRIAGE HOUSE #1 TO REMAIN
STRENGTHENED CONCRETE ANCHORAGE A-8
NEW TIE DOWN CABLES. RE-USE EXIST. 1 1/2" DIA. TIE DOWN (TYPICAL)
EXISTING CARRIAGE HOUSE #2 TO BE REMOVED
EXISTING CONCRETE TOWER T-8
EXIST. 1 1/2" DIA. TIE DOWN CABLE (TYP.)
EXISTING REFLECTOR
CONTRACTOR TO ERECT TEMPORARY STAGING PLATFORM AT CENTER OF REFLECTOR
EXISTING TIE DOWN JACKING FITTING AND BASE PLATE TO BE USED AT NEW TIE DOWN BLOCKS. TYP AT THREE LOCATIONS.
NEW TIE DOWN ANCHOR BLOCK B12
190.71' (RADIAL)
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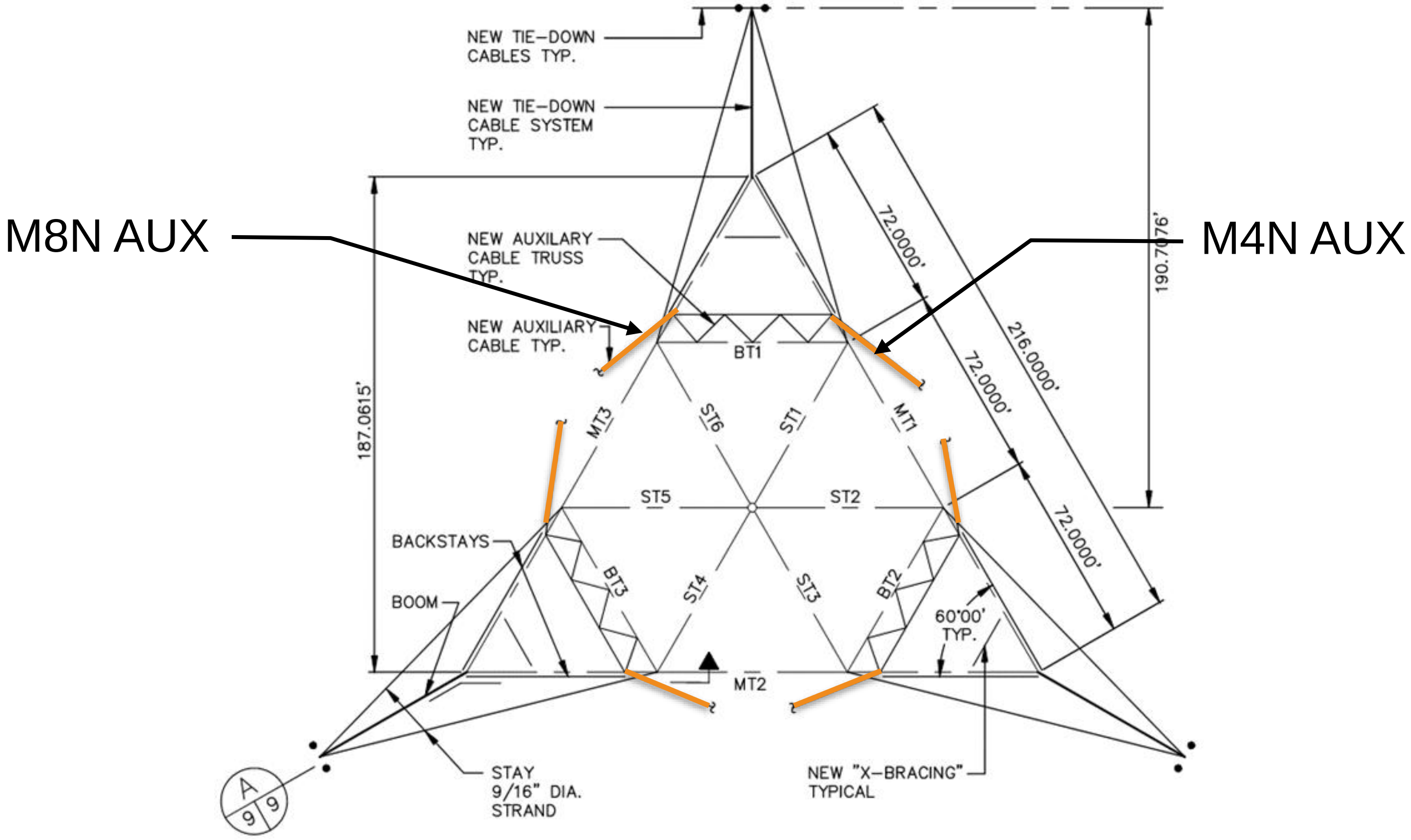
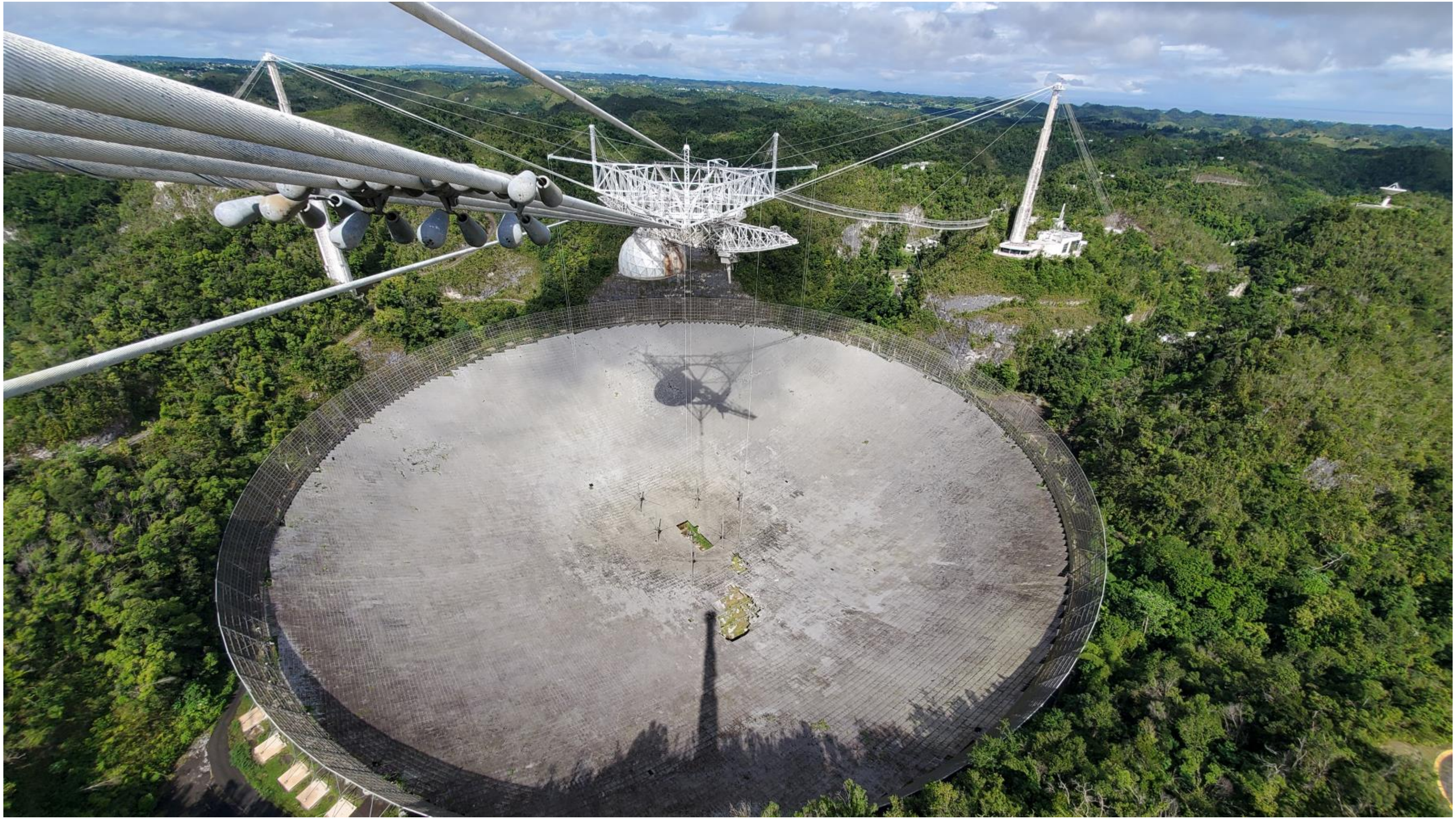
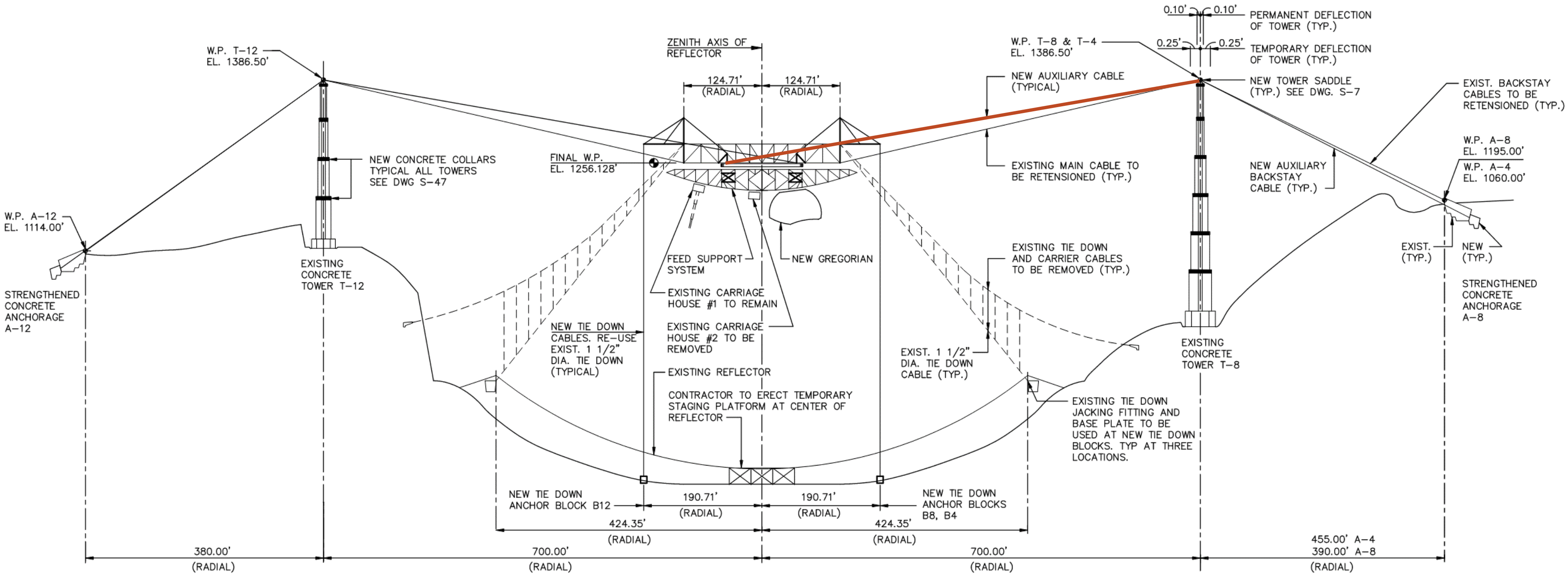
NEW TIE DOWN ANCHOR BLOCKS B8, B4
424.35' (RADIAL)
424.35' (RADIAL)
380.00' (RADIAL)
700.00' (RADIAL)
700.00' (RADIAL)
455.00' A-4
390.00' A-8
(RADIAL)


TD
12


M8N AUX
M4N AUX
NEW TIE–DOWN CABLES TYP.
NEW TIE–DOWN CABLE SYSTEM TYP.
NEW AUXILARY CABLE TRUSS TYP.
NEW AUXILIARY CABLE TYP.
BACKSTAYS
BOOM
STAY 9/16" DIA. STRAND
NEW "X–BRACING" TYPICAL
60°00' TYP.
187.0615'
190.7076'
216.0000'
72.0000'
72.0000'
72.0000'
BT1
BT2
BT3
MT1
MT2
MT3
ST1
ST2
ST3
ST4
ST5
ST6
A
9
9


GoldenEye 007 - Antenna Cradle (Movie VS Real Life)
Pause (k)
1:45 / 3:09

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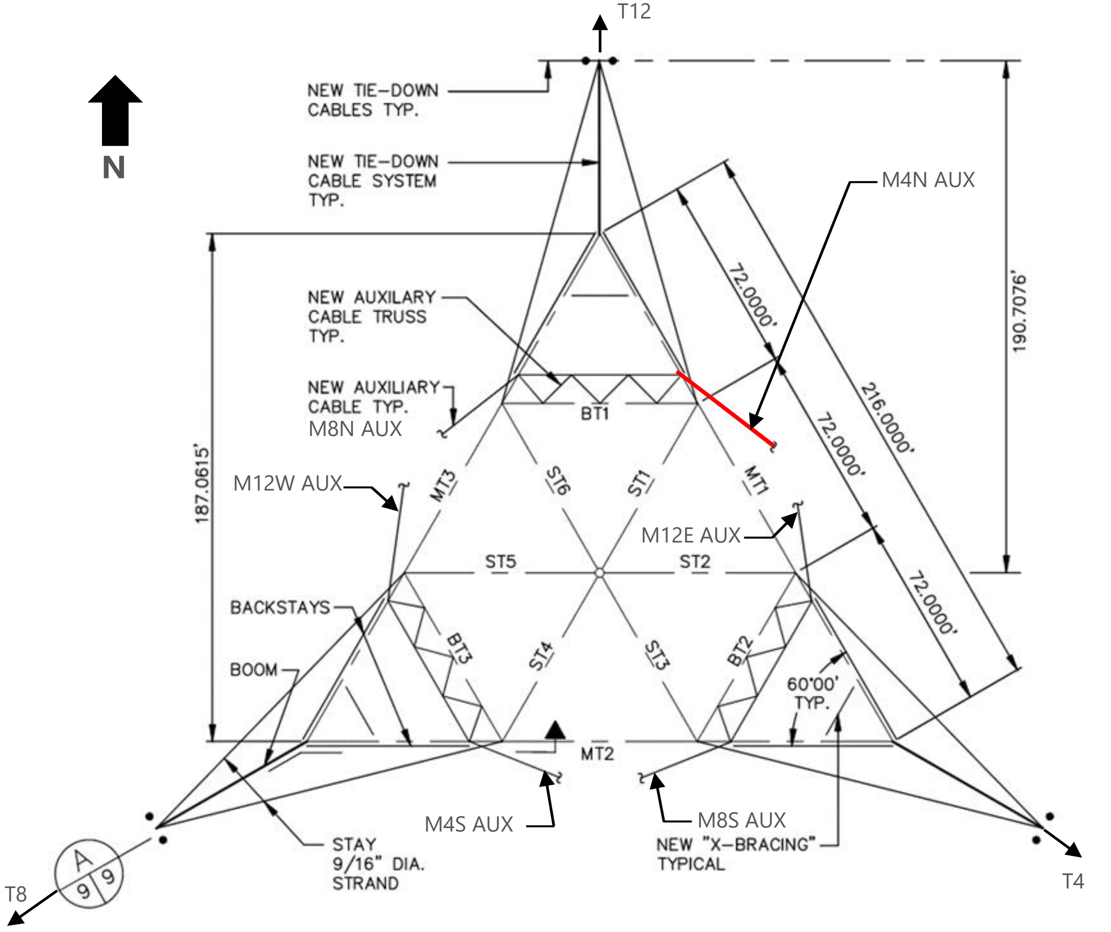
T12
N
NEW TIE-DOWN
CABLES TYP.
NEW TIE-DOWN
CABLE SYSTEM
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M4N AUX
NEW AUXILARY
CABLE TRUSS
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M8N AUX
72.0000'
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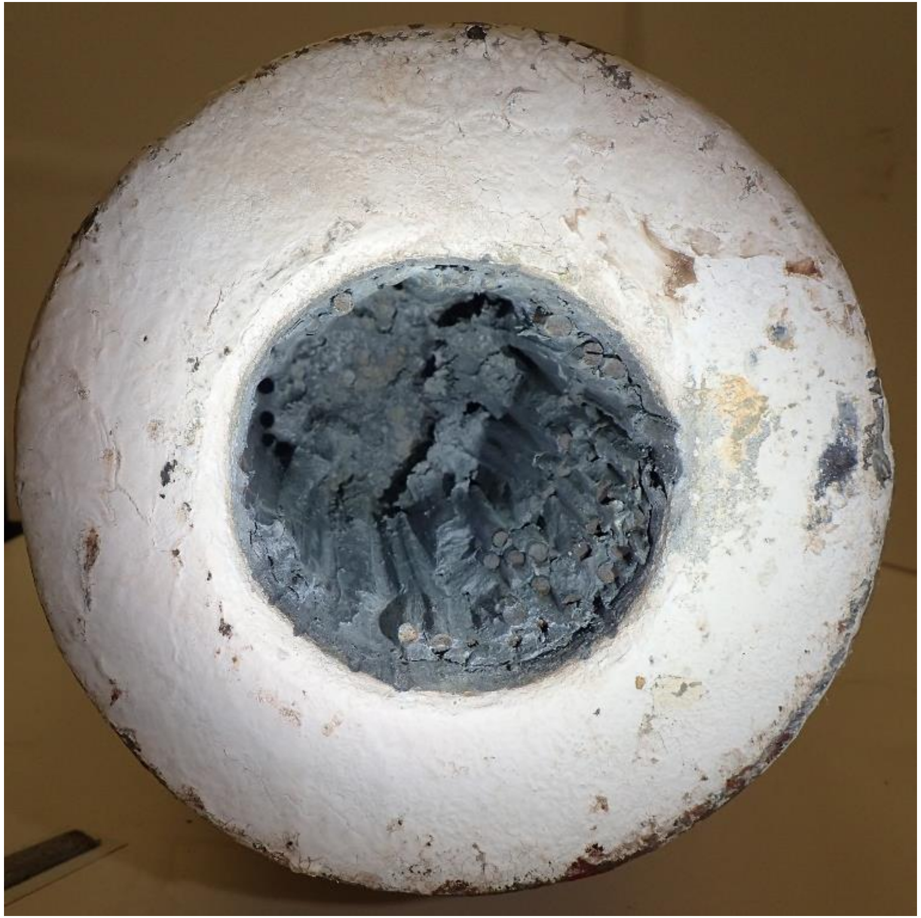
A
9
9

Photo from Arecibo Observatory

Photo from Arecibo Observatory

Photos from Arecibo Observatory



A12W AUX showing about 1 3/8-inch extension (May 2018)

A4N AUX showing 7/8-inch extension (September 2020)

M4S AUX indicating 1/2-inch extension, typical all sockets (April 2003)

M4N AUX showing 1 3/8-inch extension (February 2019)

WJE Assigned Tasks

- Assessing and Maintaining Structural Stability at Various Stages of the Investigation and Restorative Work
- Monitoring Remaining Structure
- Forensic Investigation of M4N AUX Failure

What did We Know?

- M4N AUX failed at a load that was less than half the cable's breaking strength and less than its manufactured proof test.
- Suggested a mechanism caused substantial reduction in the socket connection capacity over its service life.
- The remaining connections were strong enough to carry the loads they currently carried.

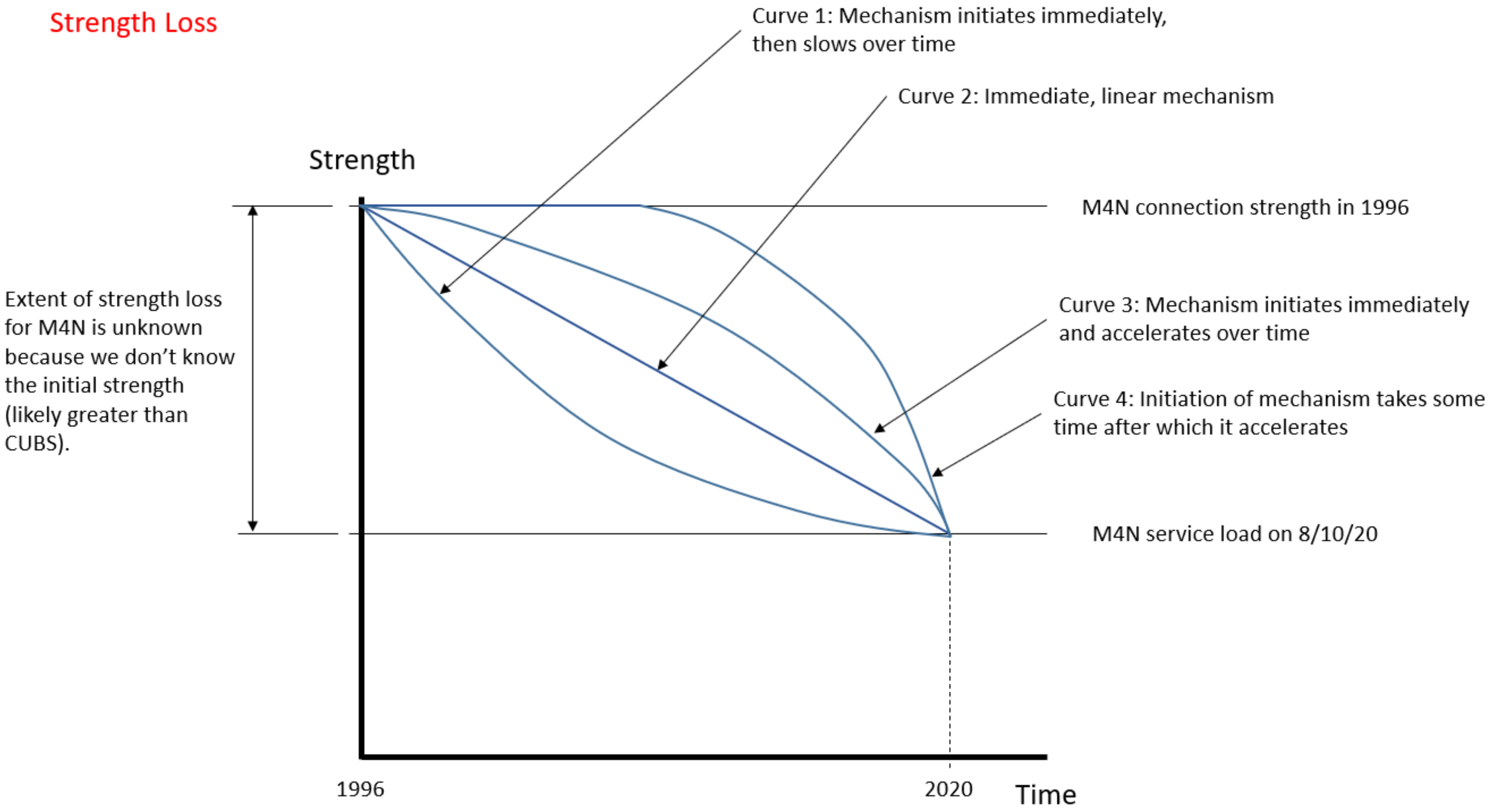
CABLE TENSIONS – STRENGTHENED CABLE SYSTEM

CABLES MK	101	102	103	104	301	302	303	304	305
NO.	12	5	5	5	6	2	2	2	6
DIAMETER	3"	3 1/4"	3 1/4"	3 1/4"	3 1/4"	3 5/8"	3 5/8"	3 5/8"	1 1/2"
MINIMUM BREAKING STRENGTH (KIPS)	1044	1212	1212	1212	1314	1614	1614	1614	290
TENSION PER CABLE (I) INITIAL TENSION UNDER ALL DEAD LOADS									
EXISTING *	527	593	541	566	—	—	—	—	—
INITIAL ERECTION	307	381	351	354	450	544	495	544	2.5
FINAL	480	543	503	514	602	728	662	727	24
(II) OPERATIONAL LOADS	493	561	519	530	615	746	678	743	59
(III) SURVIVAL CONDITION	496	577	532	540	622	769	698	760	2.5
DESCRIPTION	MAIN CABLES	MAIN BACKSTAY CABLES			AUX. CABLES	AUX. BACKSTAY CABLES			TIE DOWNS
	EXISTNG				NEW				

Why did It Matter?

- Same mechanism could have affected the remaining cable sockets; thus, current strengths of connections were highly uncertain.
- Confidence in capacities of remaining connections was not sufficient to permit workers in areas where a connection failure could prove hazardous.
- How do you safely repair the structure?

Strength Loss



Current Damaged Condition

		"Final" condition in 1992 Drawings	After failure of tower 4 auxiliary cable	After hypothetical failure of tower 12 auxiliary backstay	Minimum Breaking Strength per 1992 drawings	F.S. 1992 Drawings	F.S. After failure of Tower 4 Aux	F.S. After failure of Tower 4 Aux and Tower 12 Backstay
Tower 4	Main cables	1939	2467	2439	4176	2.15	1.69	1.71
	North auxiliary cable	606	0	0	1314	2.17		
	South auxiliary cable	606	594	589	1314	2.17	2.21	2.23
	Main backstays	2705	2657	2635	6060	2.24	2.28	2.30
	North auxiliary backstay	727	717	712	1614	2.22	2.25	2.27
	South auxiliary backstay	727	714	709	1614	2.22	2.26	2.28
Tower 8	Main cables	1940	1901	1877	4176	2.15	2.20	2.22
	North auxiliary cable	606	513	512	1314	2.17	2.56	2.57
	South auxiliary cable	606	710	705	1314	2.17	1.85	1.87
	Main backstays	2494	2474	2452	6060	2.43	2.45	2.47
	North auxiliary backstay	658	655	650	1614	2.45	2.47	2.48
	South auxiliary backstay	658	652	647	1614	2.45	2.47	2.49
Tower 12	Main cables	1938	1948	1944	4176	2.16	2.14	2.15
	East auxiliary cable	605	386	371	1314	2.17	3.40	3.54
	West auxiliary cable	606	691	678	1314	2.17	1.90	1.94
	Main backstays	2567	2479	2939	6060	2.36	2.44	2.06
	East auxiliary backstay	725	708	804	1614	2.22	2.28	2.01
	West auxiliary backstay	725	704	0	1614	2.22	2.29	

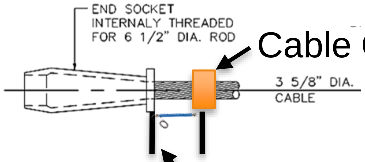
units are Kips

Risk Mitigation

- Physical Protection and Worker Positioning
- Structure Monitoring
- Analytical Modeling
- Proof Testing

Enclosure

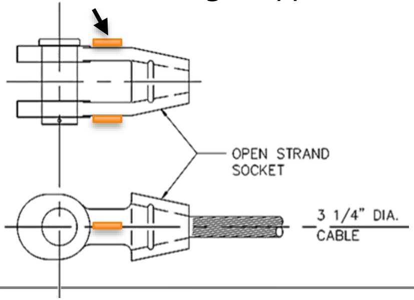
Acoustic Emissions (AE) Sensor



Cable Clamp

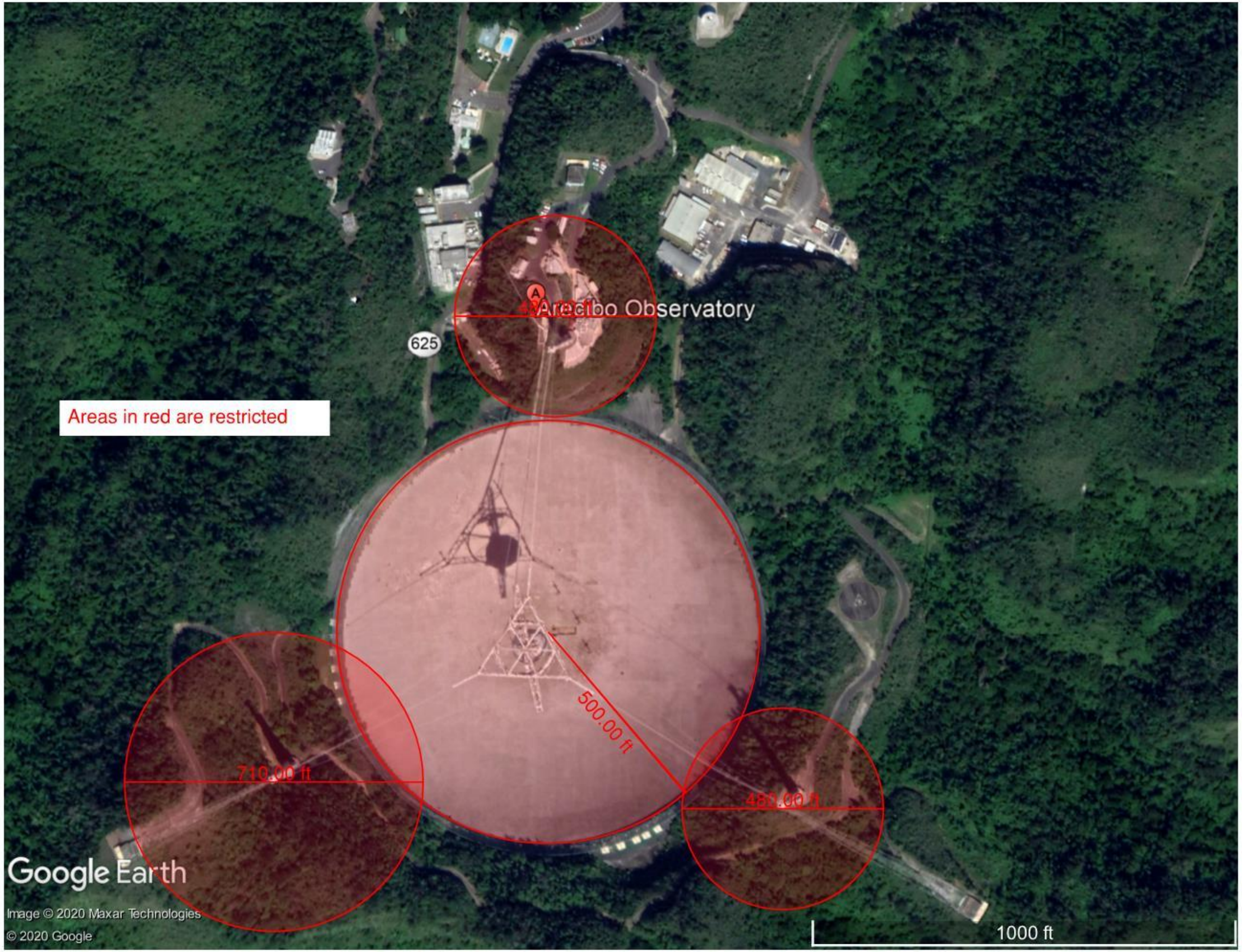
LVDT Measurement

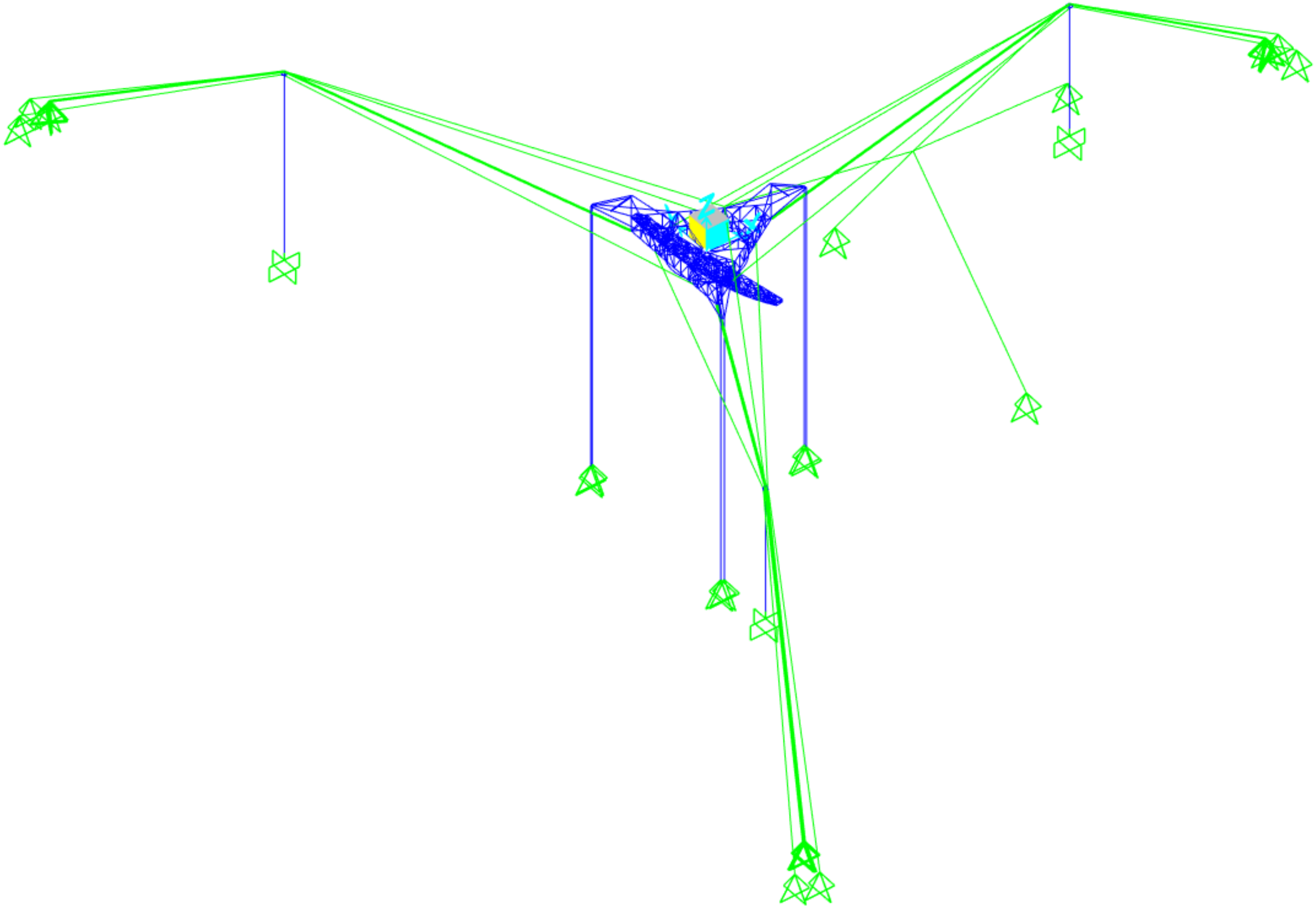
Vibrating Wire Strain Gage, Typ.



Tiltmeter


WJE
WJE



Arecibo Observatory
625
Areas in red are restricted
500.00 ft
710.00 ft
480.00 ft
Google Earth
Image © 2020 Maxar Technologies
© 2020 Google
1000 ft



2020 Study - Post-Failure

- Platform Weight: 1835 kips
- Azimuth: 260 deg. from North
- Gregorian: 8.48 deg. from Vert.
- TD4: 45 kips, TD8: 7 kips, TD12: 0 kips
- Lowest horizontal imbalance used
- Increased loads in M8S AUX and M4S AUX
- Used to calibrate FEM

Location	**Sept. 2020 Cable Tension Study (kips)**
Col. 1	**Col. 10**
Azimuth (deg)	260
Gregorian (deg)	8.48
M4*	653
M4N AUX	0
M4S AUX	611
M8*	506
M8N AUX	540
M8S AUX	749
M12*	509
M12E AUX	400
M12W AUX	688
Platform Weight	1835

Proof Testing

- Need great confidence that CDR for all elements of structure will remain above 1.0 while people are working.
- The CDR does not need to meet design standards
- Must account for the possibility of strength decreasing with time.

Proof Load Test Concepts

- Load can be removed to create an appropriate reserve capacity
- Load can be added and the removed.
- The following must remain true during any work task:

$$C_{init} - SL > D_{max} \qquad \text{Eq. 1}$$

$$C_{init} > D_{max} + SL \qquad \text{Eq. 2}$$

Where: C_{init} = Initial strength of connection

D_{max} = maximum load sustained by each connection

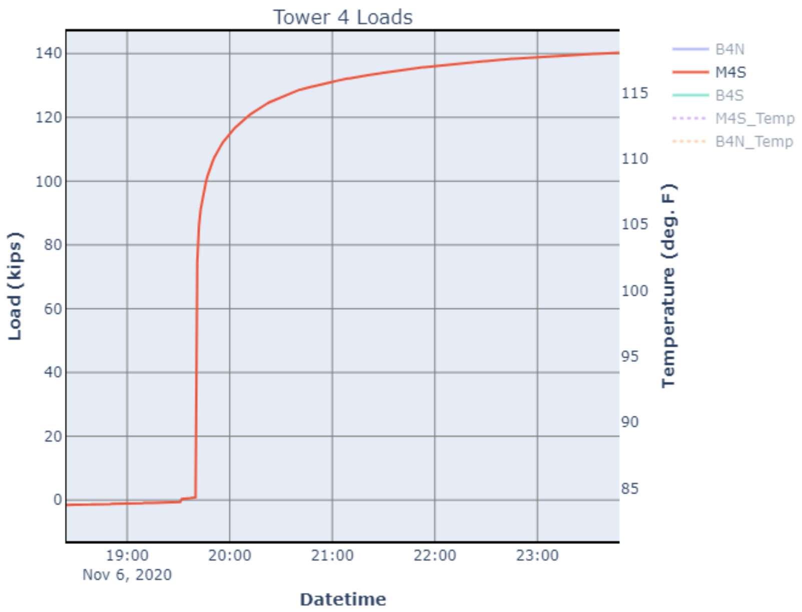
SL = Strength loss that may occur while the area is occupied


FIRE
TD
12


T4 Ax. South

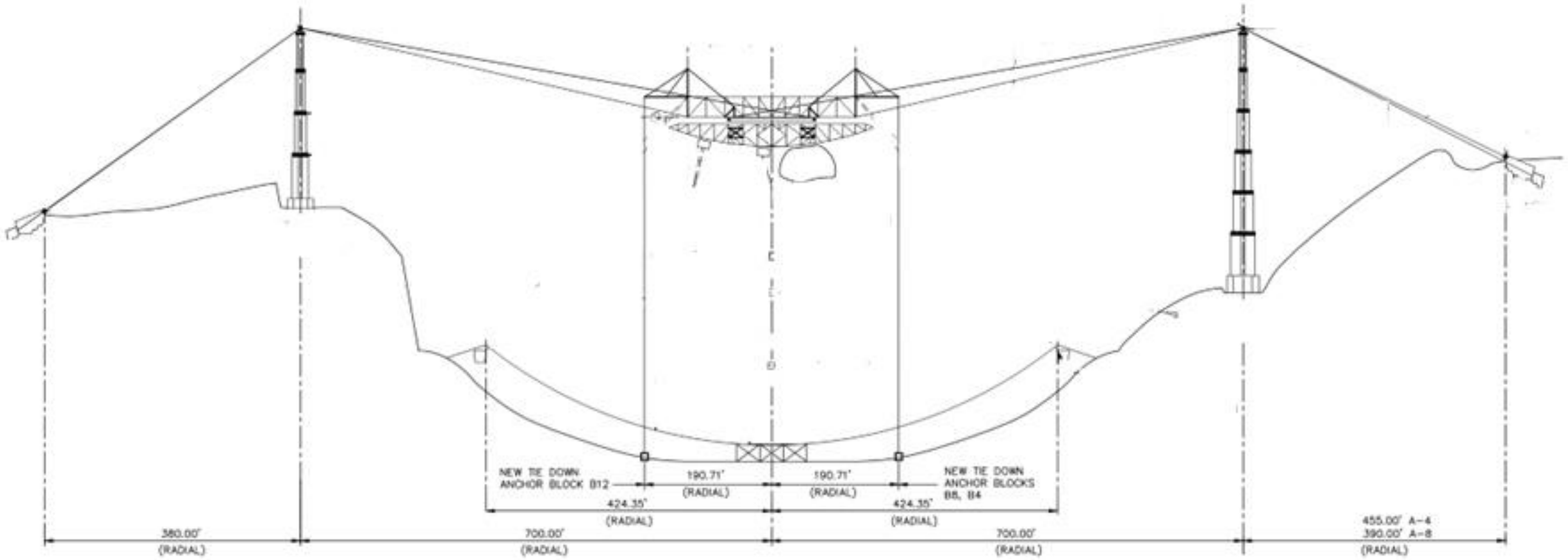
November 6, 2020, M4-4 Main Cable Failure

Estimation of November 2020 Cable Tensions




2020-11-07 06:52:47
-66.75099 +18.34323

Tower Tilt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(RADIAL)
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(RADIAL)
NEW TIE DOWN
ANCHOR BLOCKS
B8, B4
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(RADIAL)
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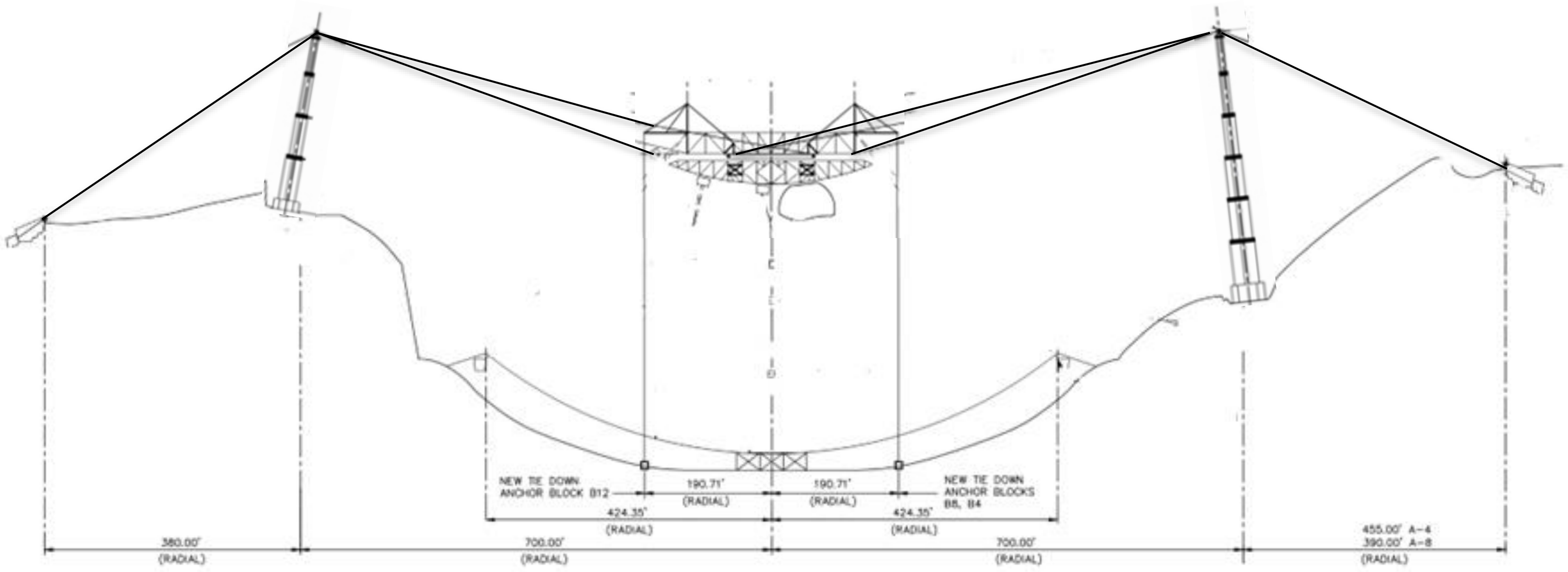
390.00' A-8
(RADIAL)

Tower Tilt



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(RADIAL)

December 1, 2020 Collapse

WJE

Forensic Investigation Team

WJE

NESC

Kennedy Space Center

Marshall Space Flight Center

The Aerospace Corporation

Industry Experts

Investigated Failure Scenarios

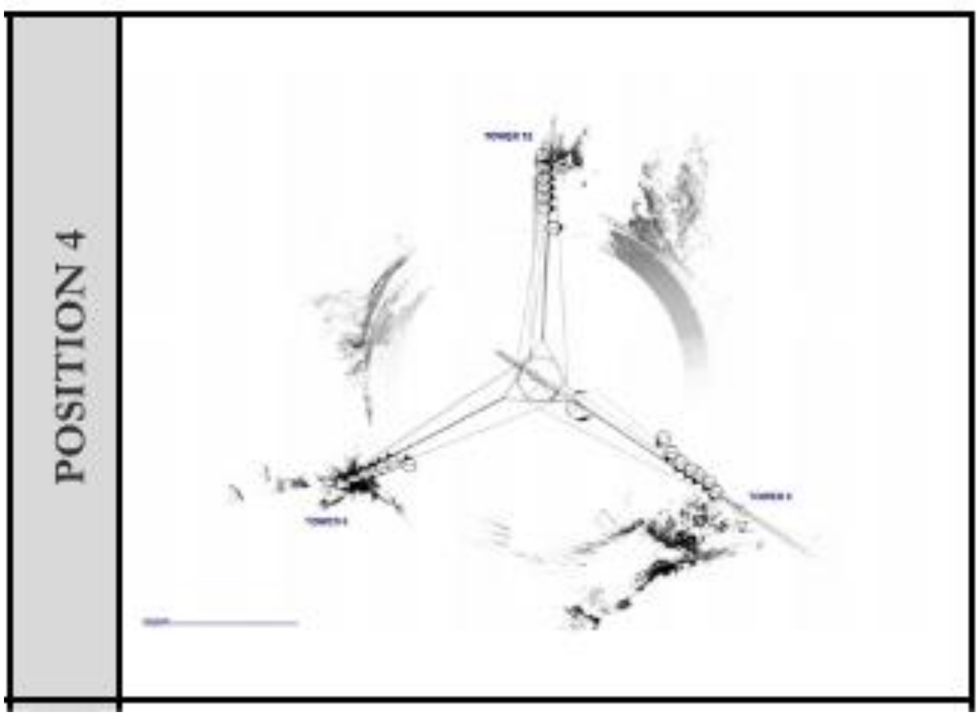
- Intact adequate assembly loaded beyond its design capacity
- Defective assembly that failed at a load less than its design capacity
- Degradation of an initially adequate assembly that eventually failed at a load lower than its design
- Degradation of an initially defective assembly that eventually failed at a load lower than its design

Investigation

- Loading
- Materials
- Fabrication
- Metallurgy
- Advanced Analysis

Loading

- Cable Tension Studies
  - 2003 Study
  - 2006 Study
  - 2017 Study
  - 2020 Study



Estimation of August 2020 Cable Tensions

- Targeted 2016 loads using Positions 1 to 4
- MN4 AUX: 583 to 688 kips
- Position 4 not credible M4N AUX
- Dead load calculated forces in Col. 6
- Platform Weight: 1811 to 1883 kips
- Same Tie-Down forces

Location ** Average of 4 main cables*	**August 10, 2020 Calculated Cable Tension (kips)**				
	Starting Position 1	Starting Position 2	Starting Position 3	Starting Position 4	Starting at Failure Location (no target forces)
Col. 1	**Col. 2**	**Col. 3**	**Col. 4**	**Col. 5**	**Col. 6**
Azimuth (deg)	30	30	30	30	30
Gregorian (deg)	10.72	10.72	10.72	10.72	10.72
M4*	523	530	537	571	506
M4N AUX	688	583	587	~~425~~	638
M4S AUX	605	583	642	627	628
M8*	498	496	512	513	500
M8N AUX	667	702	694	615	638
M8S AUX	694	613	711	698	645
M12*	501	525	549	526	509
M12E AUX	596	594	660	602	634
M12W AUX	620	556	595	600	616
Platform Weight	1811	1812	1883	1837	1812
TD4 (pair)	36	36	36	36	36
TD8 (pair)	32	32	32	32	32
TD12 (pair)	24	24	24	24	24

Telescope Operating Loads

- 1992 "Loading Condition I – Final" M4N AUX = 602 kips
- Azimuth rotated 0-360 deg.
- Tie-Downs: 24 kips per pair
- Envelope values with max. M4N AUX at 330 deg. Azimuth
- 10 to 30% higher for Aux. Mains
- 16 to 28% higher for Mains

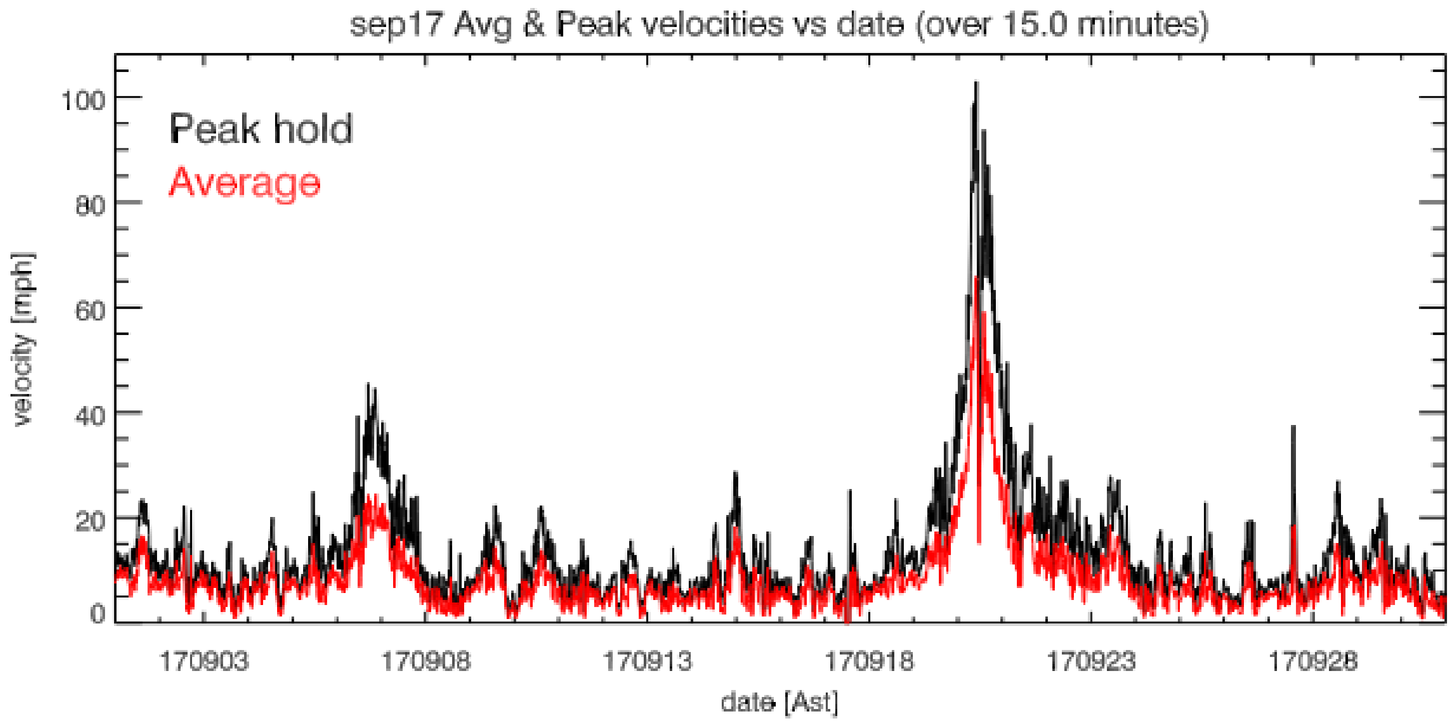
Location ** Average of 4 main cables*	1992 Design Cable Tensions Loading Condition I - Final (kips)	2016 Study Cable Tensions Starting Position 2 (kips)	2016 Study Cable Tensions Starting Position 4 (kips)	Model-Generated Cable Tensions (kips)
Col. 1	**Col. 2**	**Col. 3**	**Col. 4**	**Col. 5**
Azimuth (deg)		0 to 360	0 to 360	0 to 360
Gregorian (deg)		19	19	19
M4*	480	579	617	557
M4N AUX	602	660	~~494~~	718
M4S AUX	602	677	717	723
M8*	480	554	570	558
M8N AUX	602	781	689	715
M8S AUX	602	689	774	723
M12*	480	573	574	558
M12E AUX	602	677	688	720
M12W AUX	602	651	701	715
Platform Weight	1722	1812	1837	1812
TD4 (pair)	48	48	48	48
TD8 (pair)	48	48	48	48
TD12 (pair)	48	48	48	48

Wind Loads

- 1992 "Loading Condition I + 100 mph Winds"
- Truss Area and Solidity Values by TT
- Stowed Position
- M4N AUX loaded when winds from SE
- Peak Wind: 110 mph from Hurricane Maria, Sept. 20, 2017

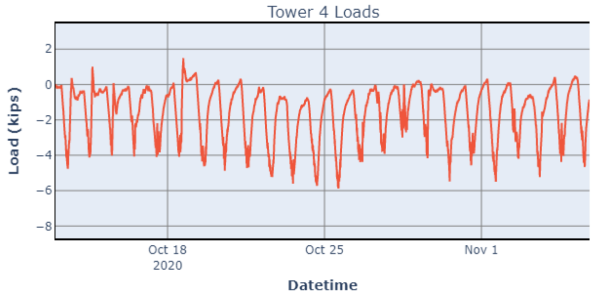
Location ** Average of 4 main cables*	**1992 Design Cable Tensions Loading Condition I + 100 mph Winds (kips)**	**2016 Study Cable Tensions Starting Position 2 (kips)**	**2016 Study Cable Tensions Starting Position 4 (kips)**	**Model-Generated Cable Tensions (kips)**
Col. 1	**Col. 2**	**Col. 3**	**Col. 4**	**Col. 5**
Azimuth (deg)		260	260	260
Gregorian (deg)		8.48	8.48	8.48
M4*	496	577	613	554
M4N AUX	622	660	~~497~~	716
M4S AUX	622	678	715	724
M8*	496	543	555	549
M8N AUX	622	770	678	707
M8S AUX	622	670	748	704
M12*	496	571	563	554
M12E AUX	622	677	681	719
M12W AUX	622	671	714	731
Platform Weight	1722	1812	1837	1812
TD4 (pair)	5	0	0	0
TD8 (pair)	5	0	0	0
TD12 (pair)	5	0	0	0

Hurricane Maria Wind Loads

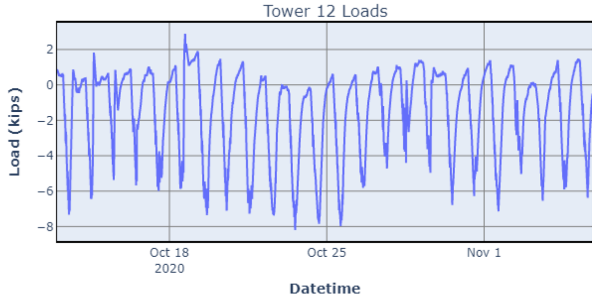


Thermal and Vibration Loads

- Instrumentation installed by WJE by October 11, 2020
- 72 deg. F to 92 deg. F
- Daily tension variations 4 to 8 kips
- No evidence of significant vibrations



M4S AUX



M12W AUX

Loading Findings

Design Overload

- Weather, Seismic, and Operating Loads were normal on Aug. 10
- 1,314-kip original design breaking strength of cable
- Load in M4N AUX likely between 580 kips and 690 kips
- Loads may have exceeded 657-kip proof load
- Hurricane Maria may have contributed to additional zinc extension
- Prior to the failure, no evidence socket was loaded near its nominal strength

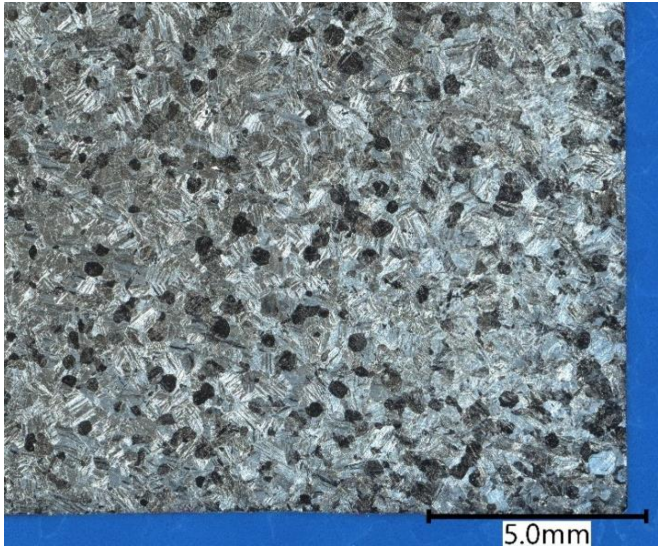
Loading Findings

Operating Loads

- Actual supported weight about 7% greater than in Gregorian upgrade drawings
- Analytical modeling revealed maximum cable forces 10-30% higher for Auxiliary Main Cables and 16-28% for Main Cables
- Daily thermal load fluctuations about 8 kips or 1.3% of Loading Condition I and not a contributor to fatigue
- Dampers installed, with any high frequency vibrations not expected to generate damaging levels of stress.

Materials

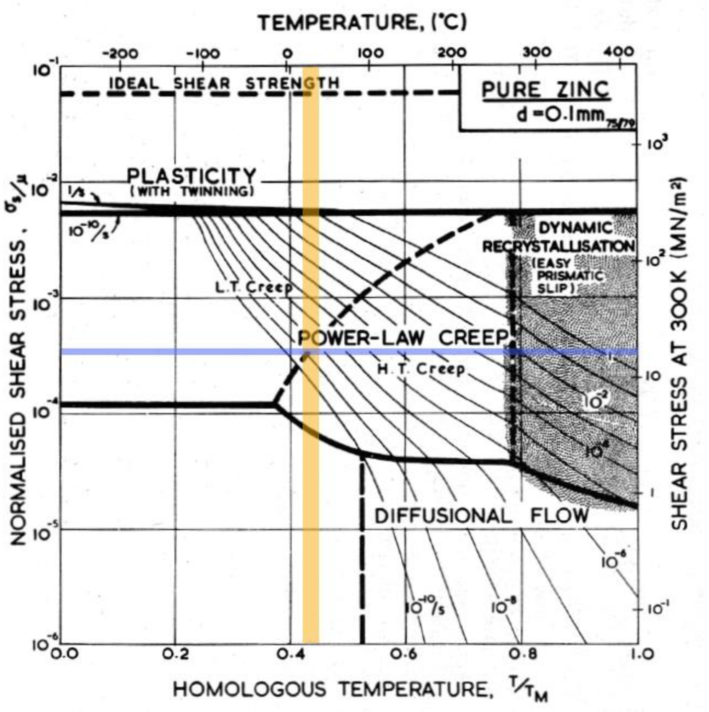
- Zinc Material Property Studies
  - Tensile Tests
  - Shear Tests
  - Compression Tests
  - Zinc Chemistry
  - Zinc Creep Tests
  - Metallographic Examination of Zinc Creep Specimens



Zinc Creep Studies

Orange band represents a temperature range of 20–40 °C (68–104 °F).

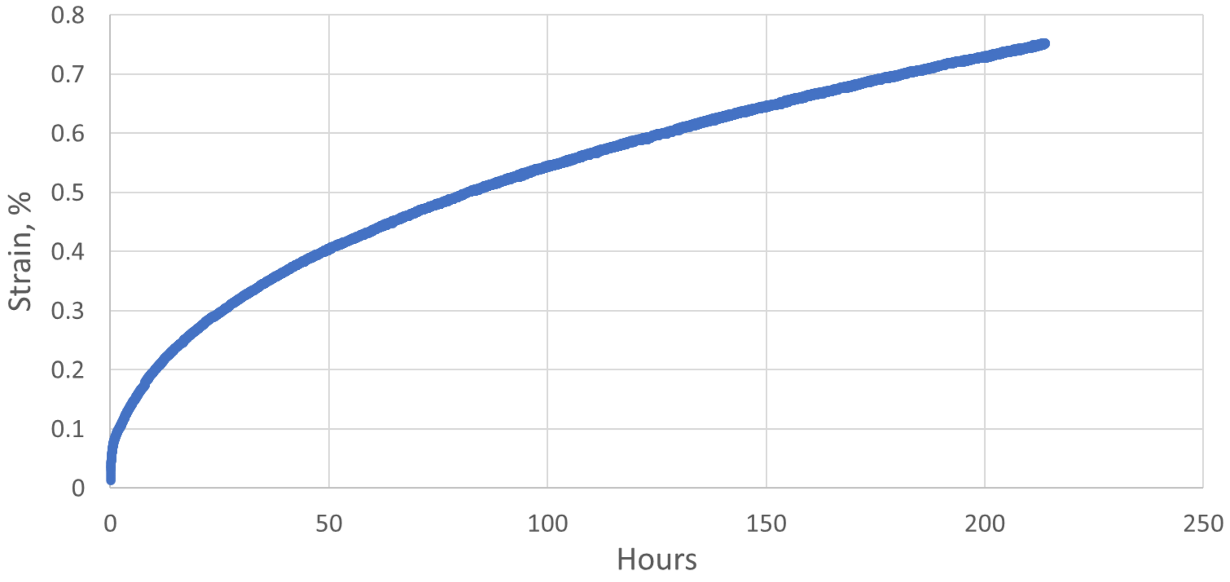
Blue line represents a resolved shear stress of 16 MPa (2,310 psi)



Zinc Creep Studies

Specimen B4

- T=100 °F
- σ_1=1,450 psi
- $\dot{\varepsilon}_1$ = 4.8E-09
- σ_s= 837 psi
- $\dot{\gamma}$ = 8.3E-09



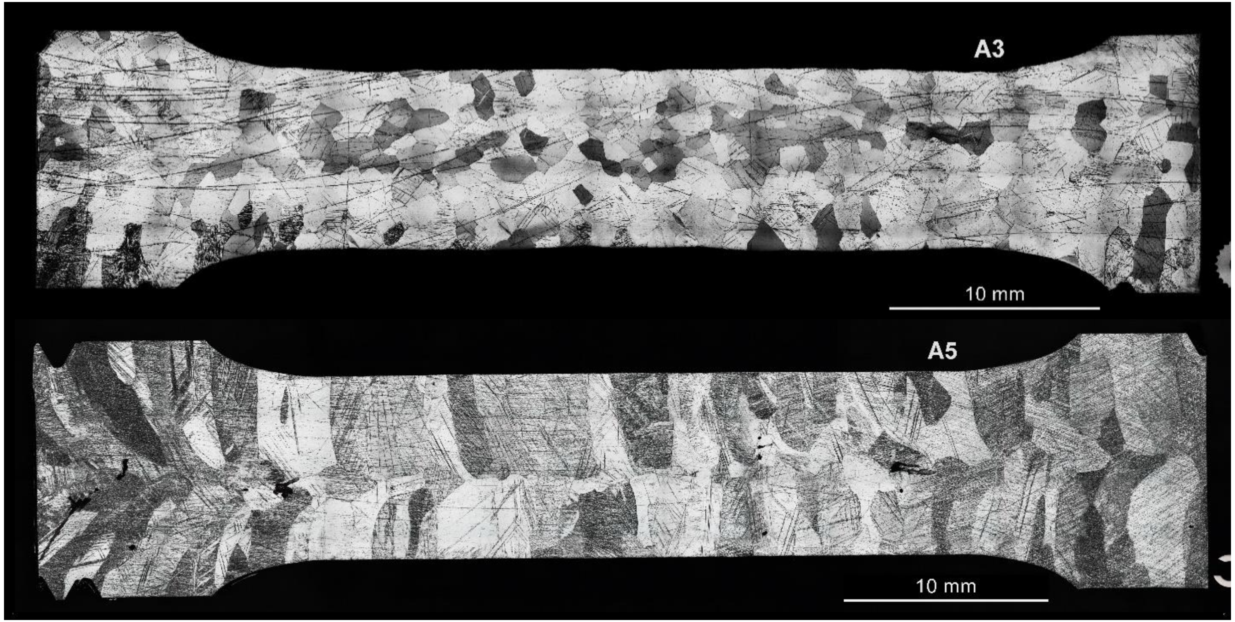
Metallographic Examination of Zinc Tests

Specimens A3

- T=200 °F
- σ_1=1,450 psi
- A3=214 hrs@ 6.4%

Specimens A5

- Untested



Materials Findings

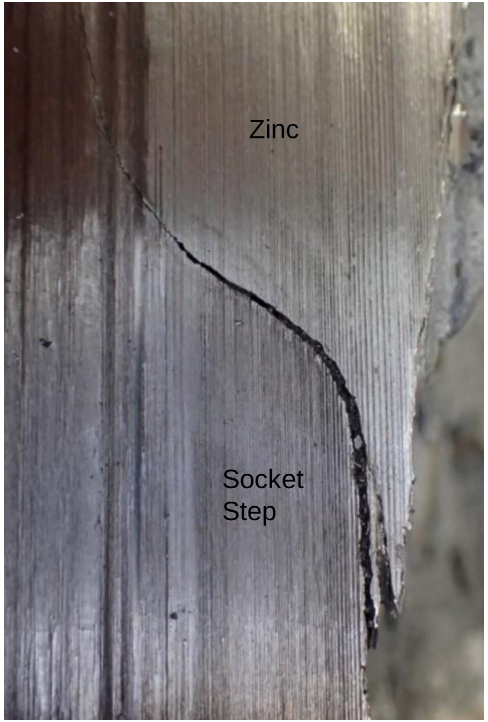
Zinc Spelter Properties

- Unlike other metals used in this fabrication, at room temperature, zinc experiences 42% of its absolute melting temperature
- This property enables zinc to continuously nucleate and form new grains with plastic flow
- Confinement pressure in the spelter suppresses zinc cleavage protecting it from low-ductility behavior and enabling it to plastically deform and strain harden
- Coarse grain structure observed is generally beneficial to creep resistance

Materials Findings

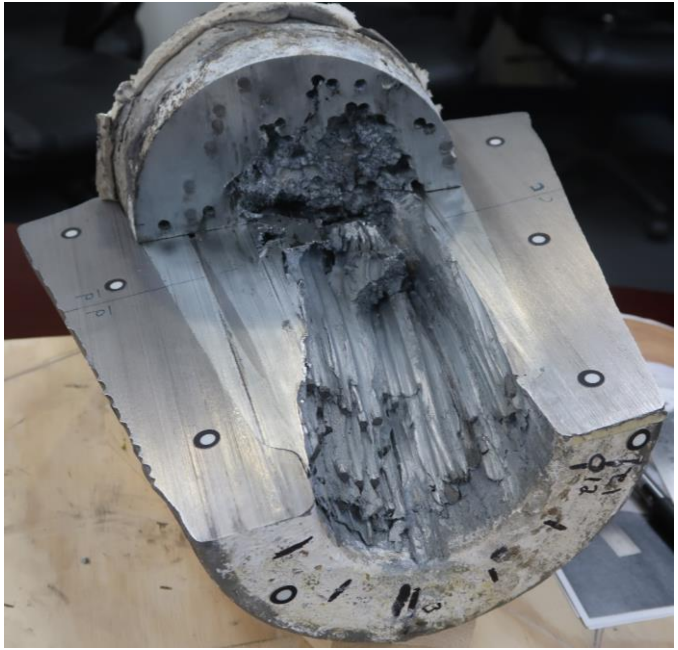
Socket Construction

- The open socket for M4N AUX conformed to the construction documents
- There were no identified defects with the casting
- The small step at the front of the socket has been discontinued as it was attributed to excessive bending in the perimeter wires and consistent with advanced modeling results
- Sockets with steps have performed reliably



Fabrication

- Socket Observations
  - Voids
  - Distress and Atypical Features
  - Wire Distribution and Identification
  - Corrosion
  - Chemistry



WJE

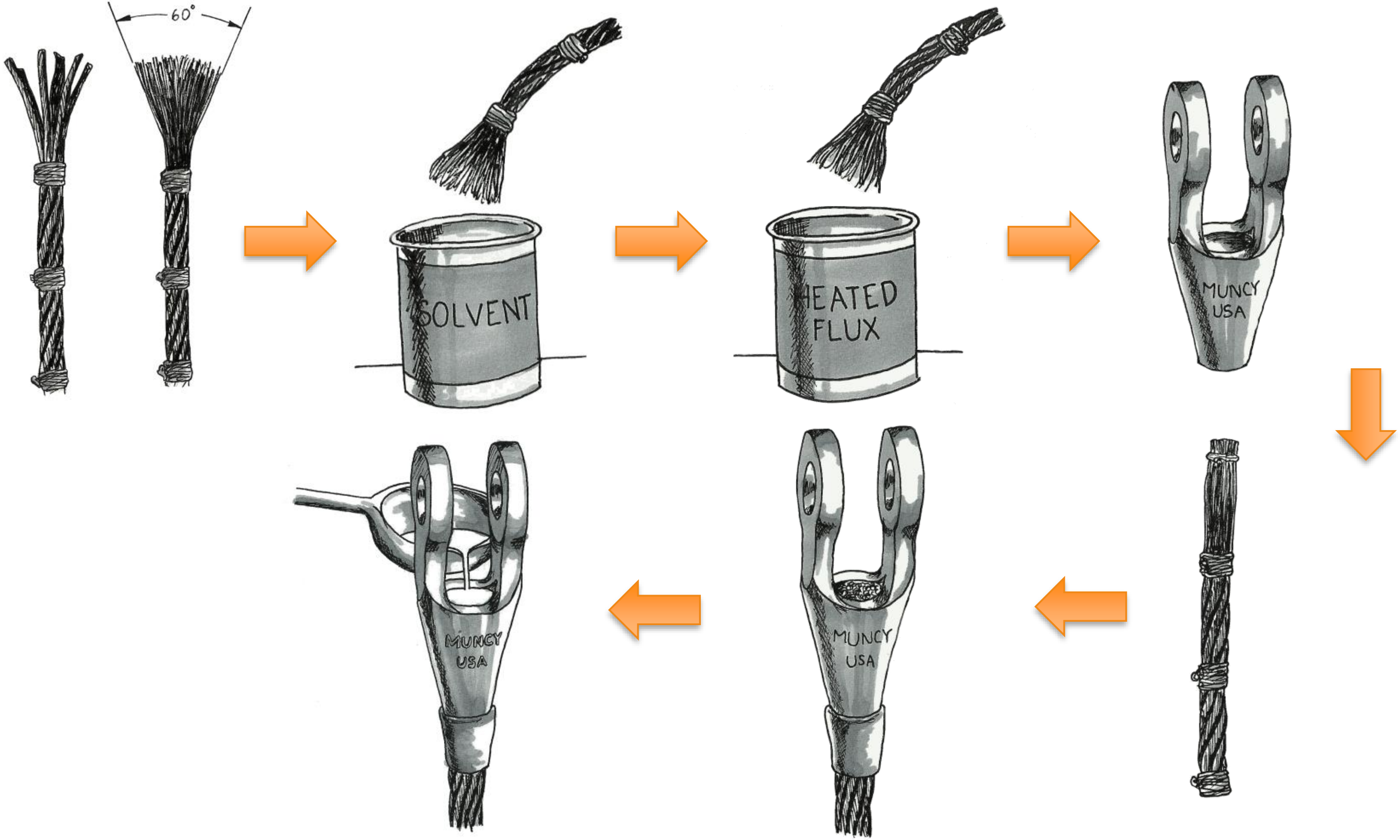
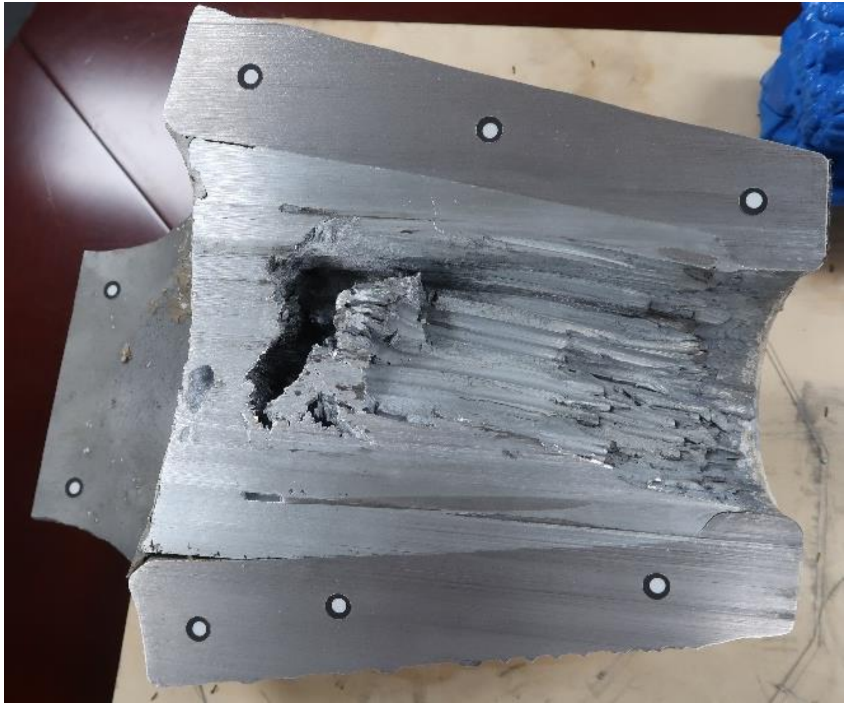


Photo from Muncy Industries

Fabrication Findings

Wire Surface Preparation

- Often associated with failures during proof testing
- Bond strength strong enough to permit seating of the spelter within the socket to create confining force
- Once seated, surface preparation not a significant factor to socket performance



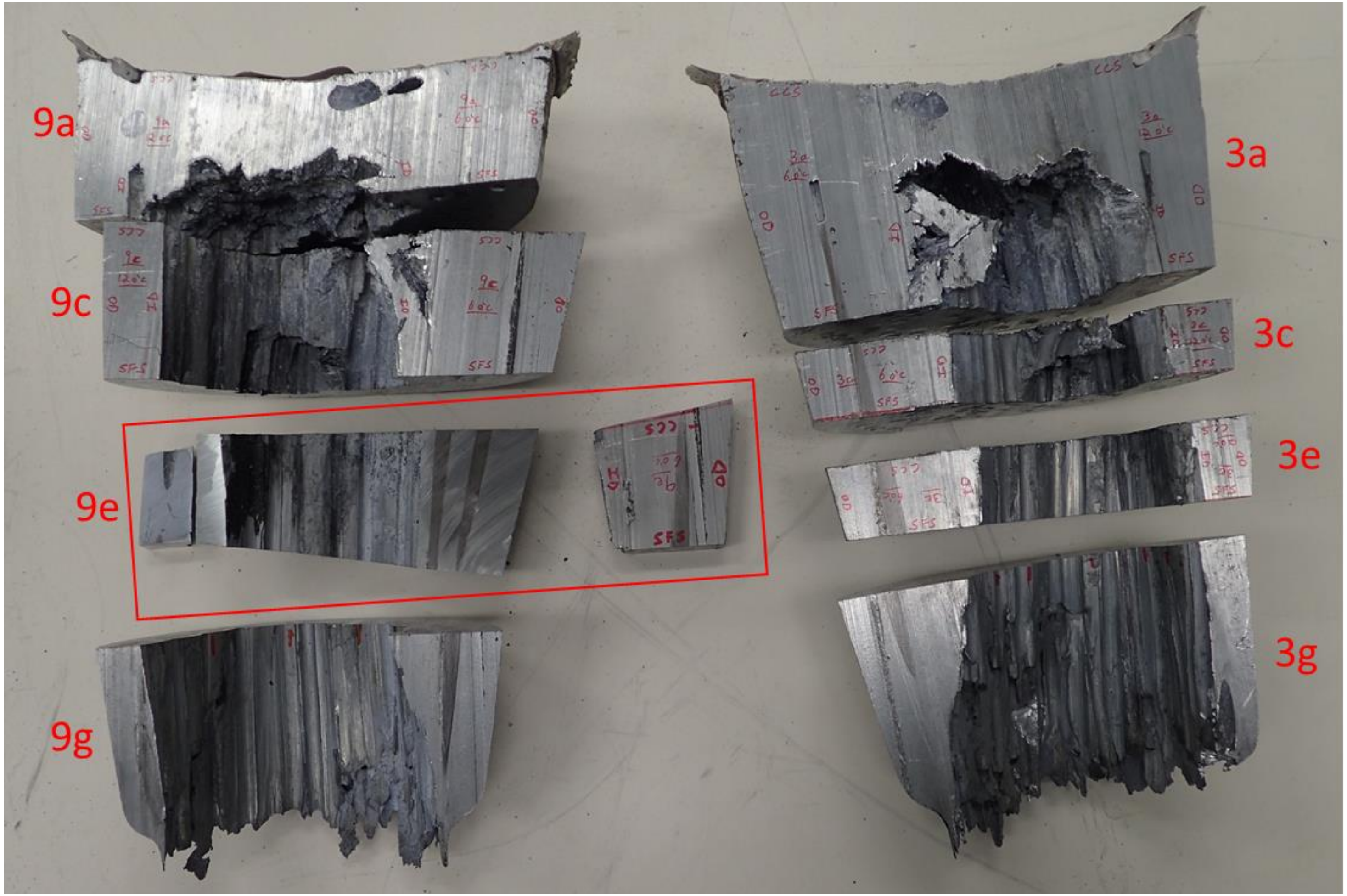


Photo from KSC

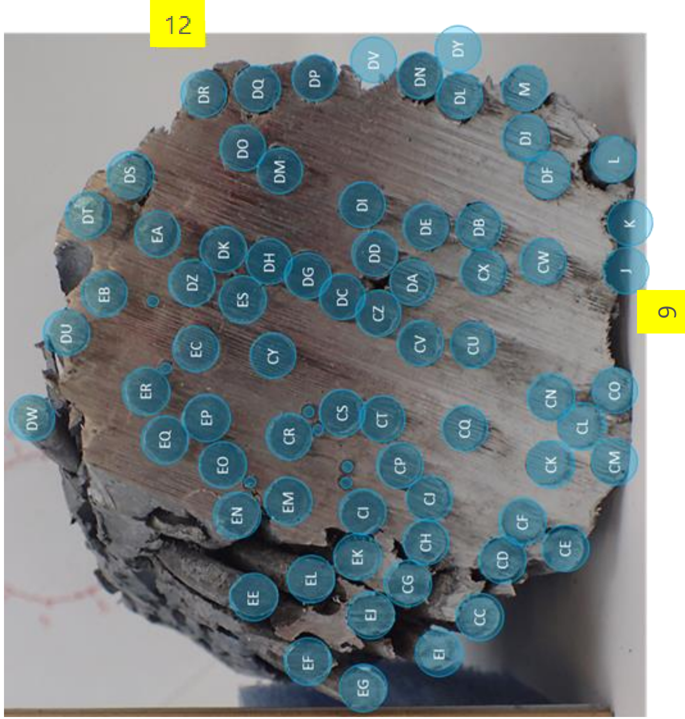
Voids

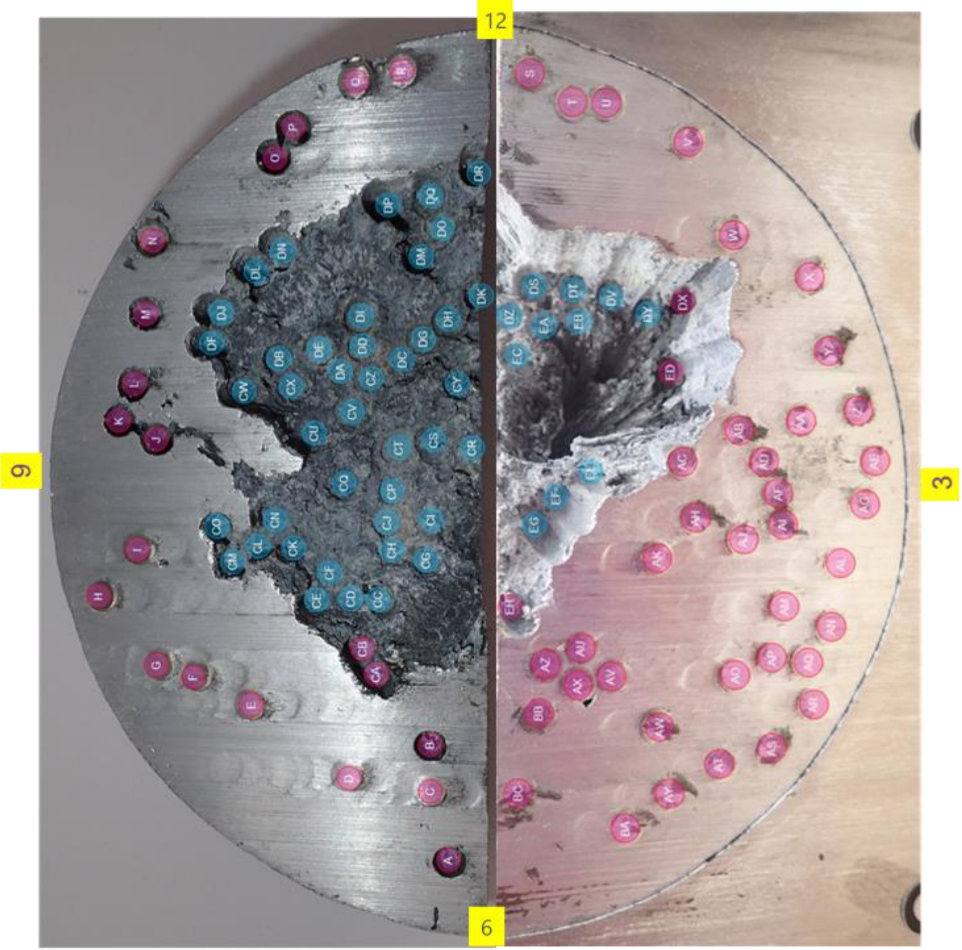
Fabrication Findings

Spelter Consolidation

- Voids in zinc are common, particularly at the top
- Largest voids were located near the top of the socket which appears to have minimal effect on performance
- Large void near top possibly created when movement of spelter under load caused separation

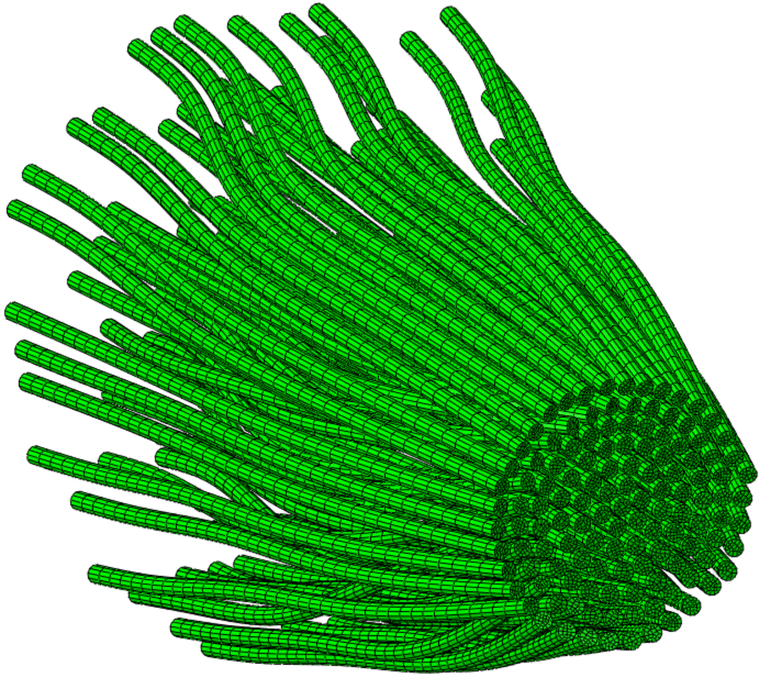
Wire Distribution and Identification

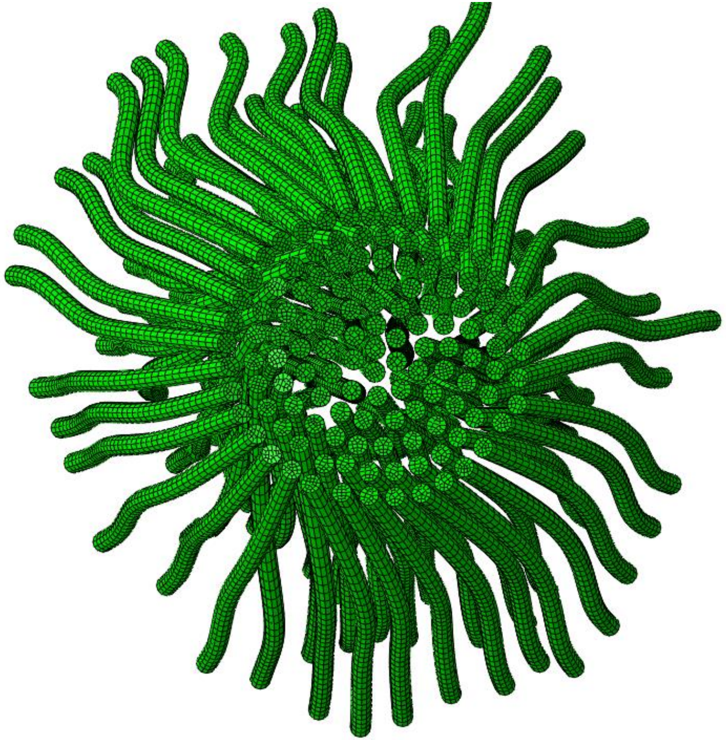




Photos from KSC

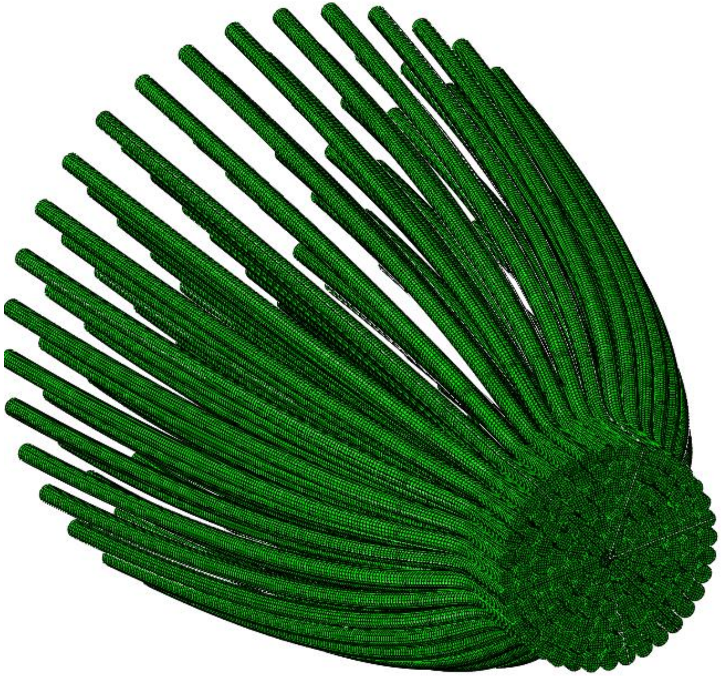
Wire Distribution and Identification

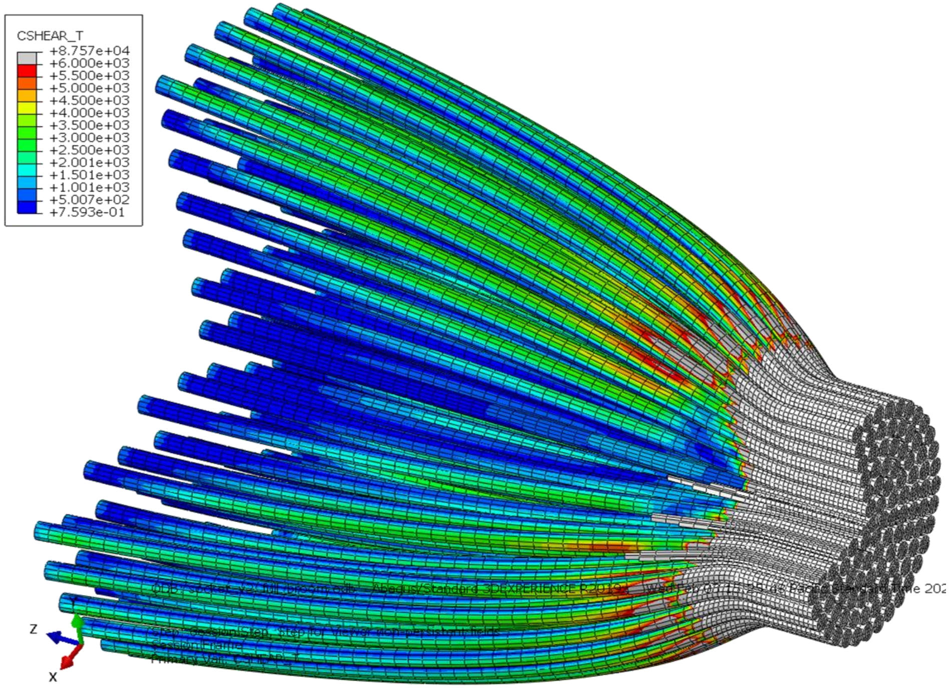




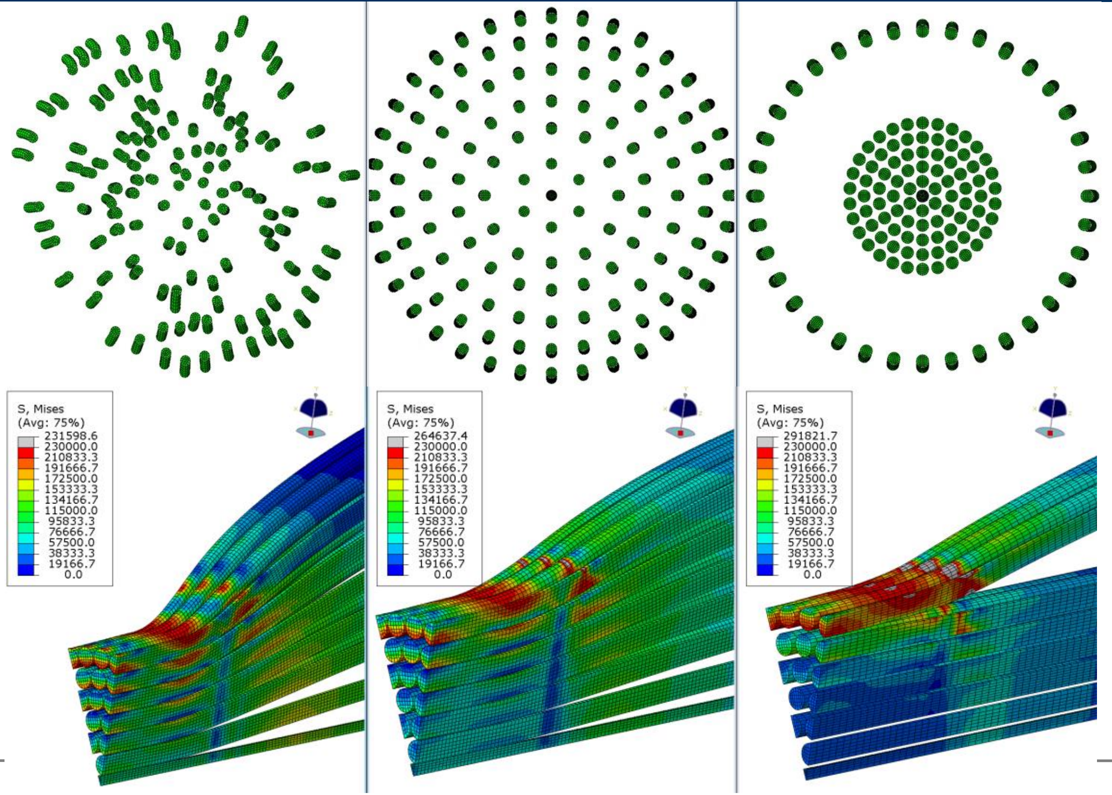
Graphic from Aerospace Corp.

Advanced Analysis of Socket





Advanced Analysis of Socket



Graphic from Aerospace Corp.

Fabrication Findings

Brooming

- Improper or uneven brooming can adversely affect distribution of wire stresses
- Thus, variations in brooming can result in variations in socket performance
- Industry experts believe M4N AUX to have been broomed within industry norms

Metallurgy

- Optical and SEM Fractography of Wire Breaks
  - Cup-Cone Wire Breaks
  - Slant Shear Wire Breaks
  - Hydrogen Assisted Cracking

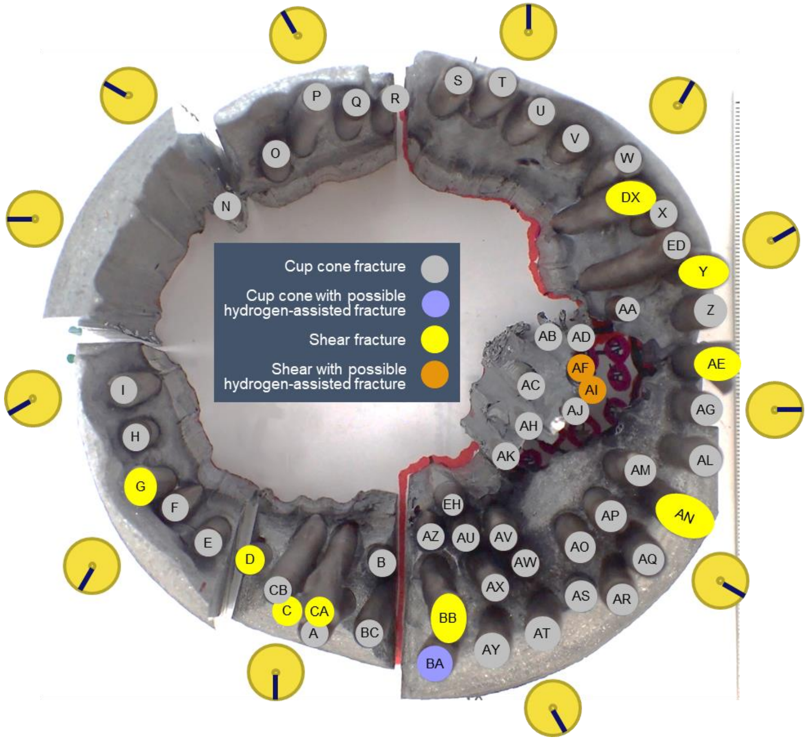
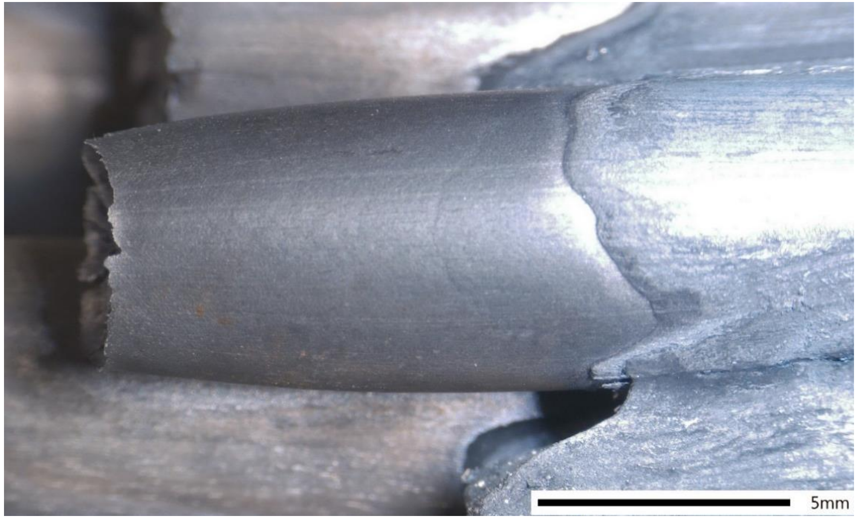


Photo from KSC

Wire Fractures

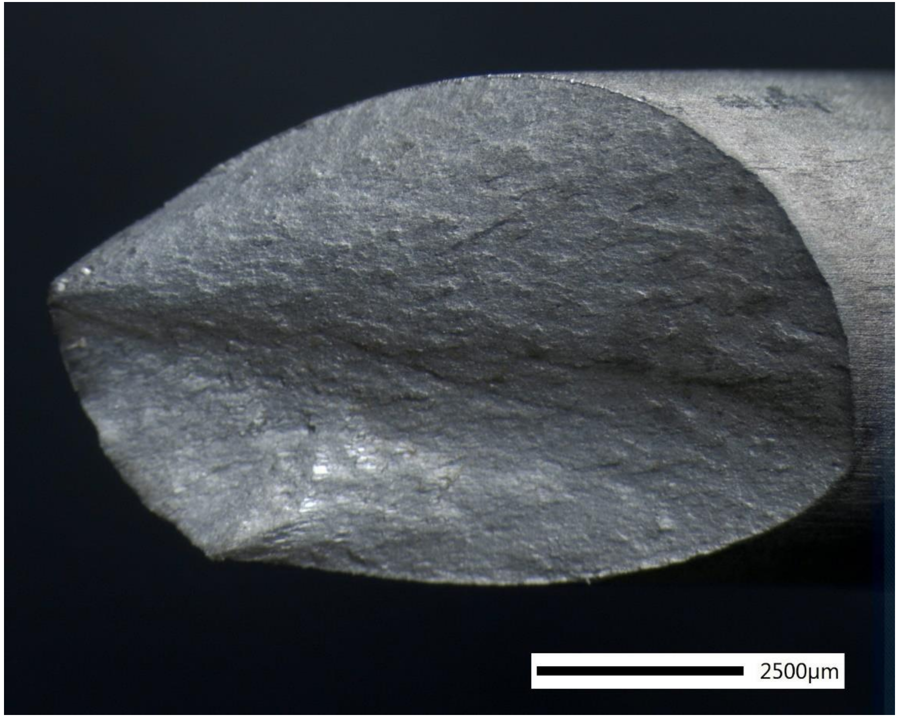
Photos from KSC

Cup-Cone Fracture



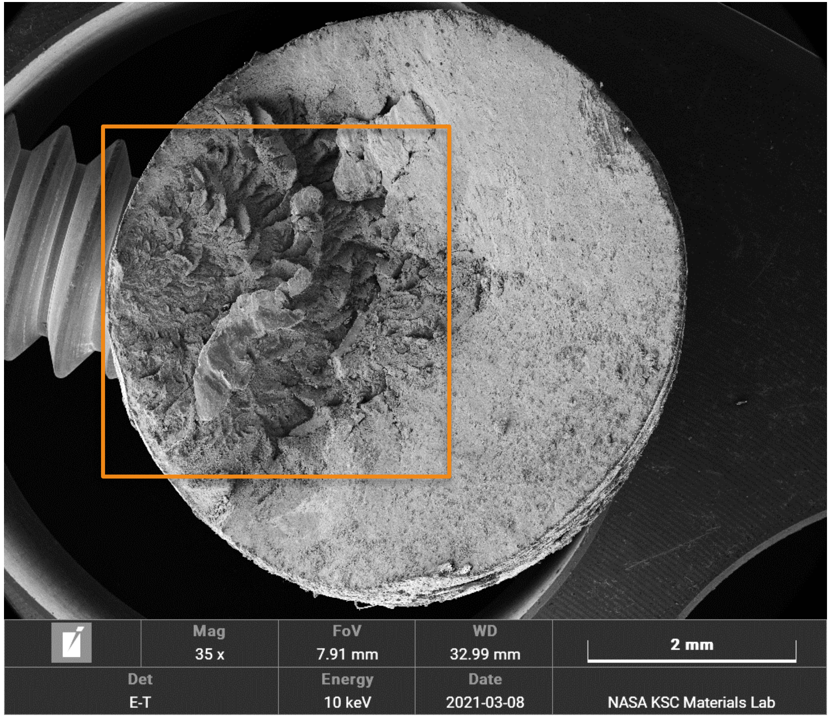
Wire EH

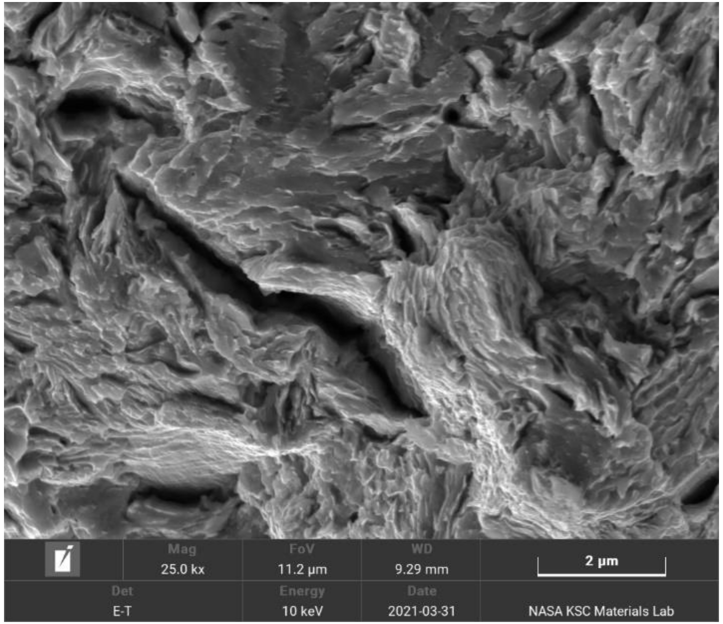
Slant Shear Fracture



Wire G

Hydrogen Assisted Fracture





Wire AF Shown, Wire AI and Wire BA similar HAC

Socket Strength Degradation Findings

Fatigue

- No evidence of striation-forming high-cycle fatigue crack growth
- Nearly all wires failed as cup-cone or slant shear tensile overload fractures
- Possibility of low-cycle fatigue but similar and nearly indistinguishable from simple overload

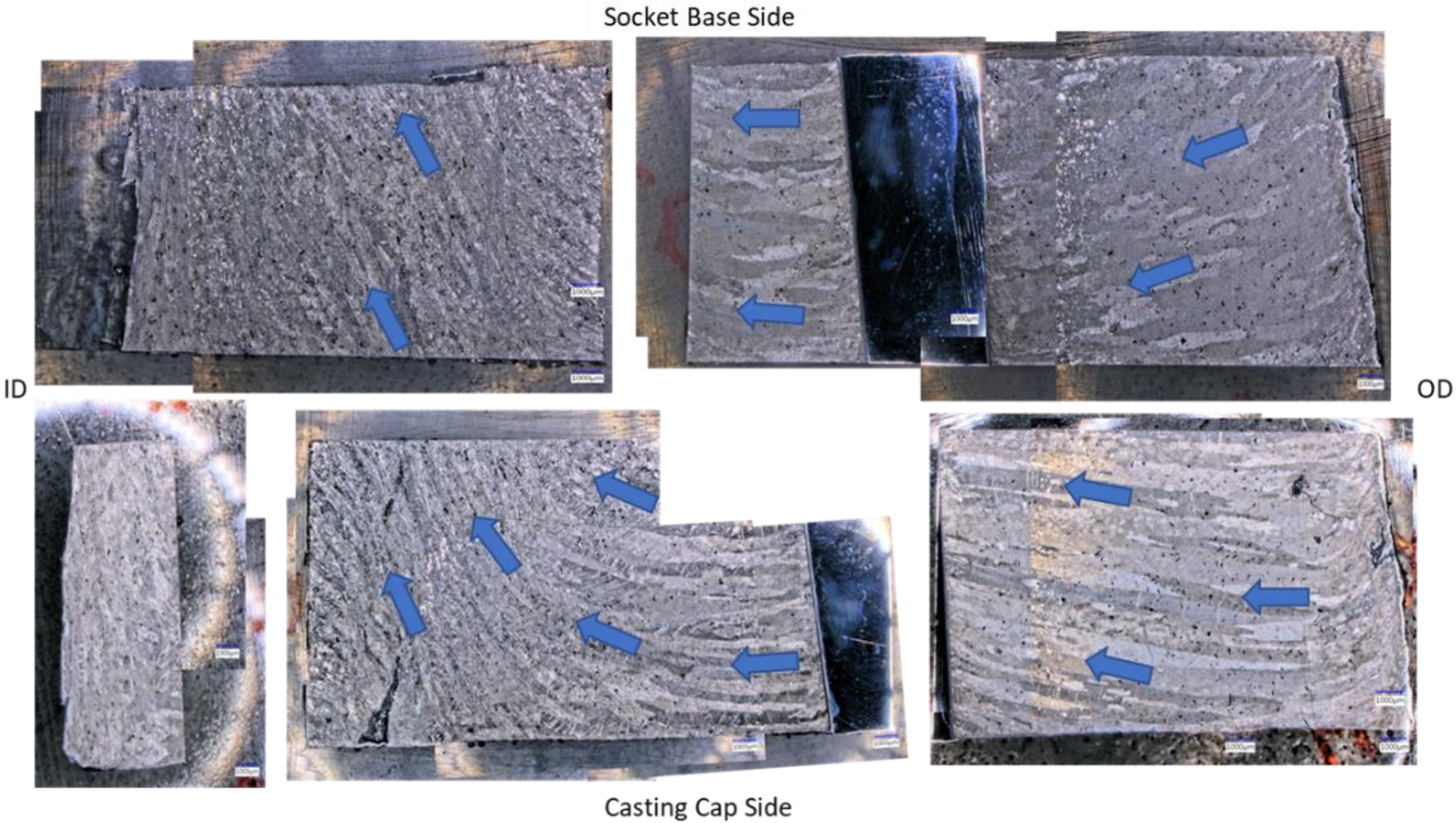
Socket Strength Degradation Findings

Embrittlement

- Cathodic hydrogen produced as a biproduct of corrosion
- Three wire fractures associated with HAC failure

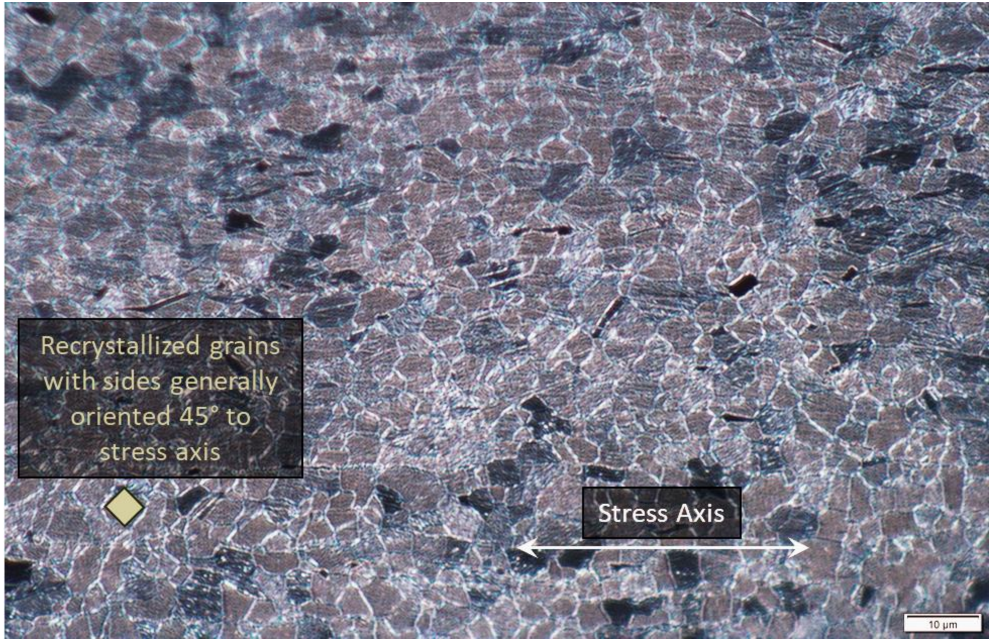
Metallurgy

- Zinc Metallography and Fractography
  - Overall Grain Structure
  - Cavity Fracture
  - Oxidation of Crack Faces
  - Deformation Effects



Photos from KSC

Deformation Effects

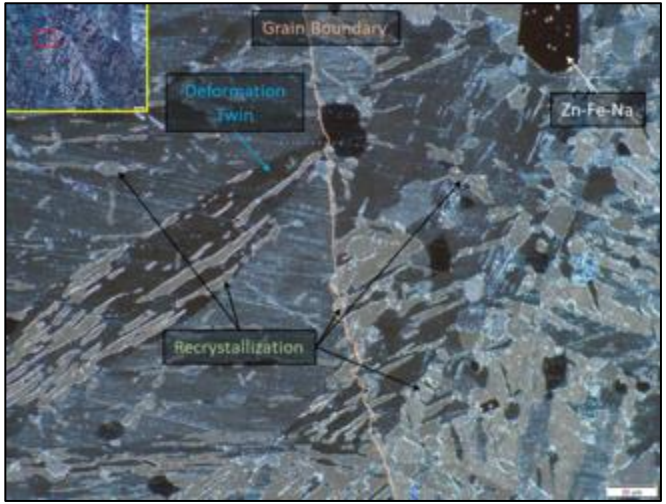


Photos from KSC

Socket Strength Degradation Findings

Creep

- Tensile creep tests at 100 and 200 deg. F exhibited secondary strain rates comparable to published values
- Even when adjusted for lower temps, strain rates over 25 years could accumulate very large plastic shear strains



- Microstructural evidence of creep observed in spelter zinc
- Small changes in zinc stress greatly affect creep strains

Photo from KSC

Investigation Findings

Failure Scenario

Conclusions

Cause

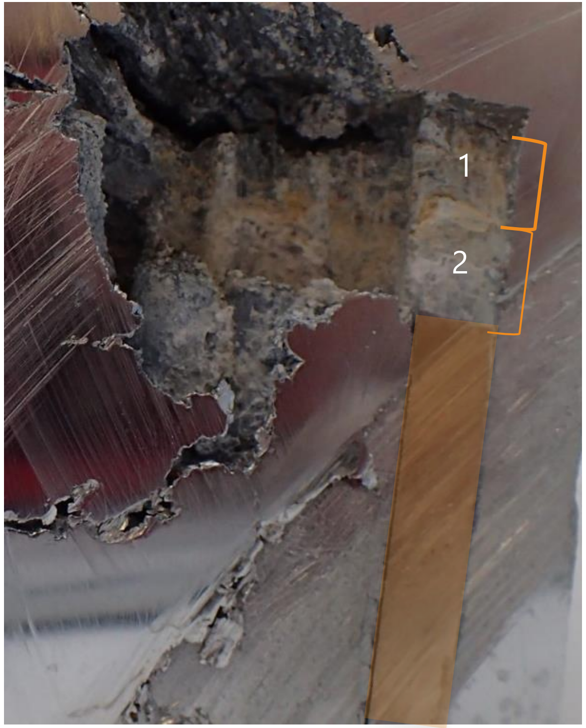
Industry Recommendations

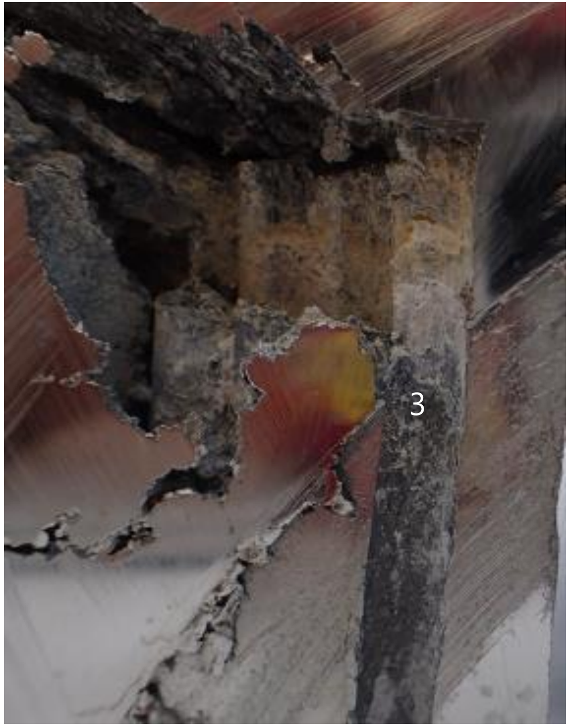
Failure Scenario

- Failure of M4N AUX socket began with initiation of creep in the zinc spelter once cables fully loaded
- The effects of creep shifted load from inner wires to outer wires
- Outer wires initially subjected to higher stresses due to bending making them likely locations for initial wire failure
- Creep in zinc can decrease its strength and its ability to transfer load from inner wires to outer wires
- Initial wire breaks were closely followed by other nearly critically-stressed wires and then pull-out of remaining interior wires

Failure Scenario

- (1) Limited zinc oxidation from slip due to proof testing and zinc seating
- (2) Presence of steel corrosion from wire end without galvanizing indicates wire in this position for long time
- (3) Second movement consistent with additional observed zinc extension





Photos from KSC

Conclusions

- M4N AUX suddenly failed under normal operations and typical weather conditions
- All socket and cable materials met the specifications
- Fabrication of socket was consistent with typical workmanship and construction practices
- No evidence the loading that night exceeded the design-specified ultimate capacity of the cable
- Operating loads on structure were 10% to 30% greater than listed in design

Conclusions

- Platform loads constituted approximately 90% of sustained loads on the cable over the past 25 years
- Sustained loads were approximately half of the specified ultimate capacity
- This level of sustained loading is uncommon in civil structures utilizing cables

Cause

- M4N AUX failed because creep-related effects over 25 years reduced the capacity of the socket until it could no longer carry the service loads
- Consistent with industry practices, the long-term degradation of the socket's capacity due to creep was not considered in the Gregorian dome upgrade or subsequent structure inspections and evaluations

Failure Scenario 1 - An intact, adequately fabricated assembly was loaded beyond its design capacity (due to a previously unknown design defect that substantially reduced its nominal capacity).

Industry Recommendations

- In order to mitigate the detrimental effects of creep, the sustained shear stresses in a zinc spelter should be limited
- Considerable physical testing and advanced analysis required to develop practical design methods.
- In the absence of an updated design methodology that explicitly considers creep effects, sustained portions of total design demands should be kept below those typically applied to cables that have performed well for decades.
- Using cables with larger numbers of smaller wires may also be beneficial.

Thank You

Questions