Arecibo Observatory Auxiliary M4N Socket Termination Failure Analysis

NASA Engineering & Safety Center
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https://ntrs.nasa.gov/citations/20210017934

Team List

Collaborators:

- NASA Engineering & Safety Center (NESC)
- NASA Kennedy Space Center (KSC)
- Wiss, Janney, Elstner Associates, Inc. (WJE)
- NASA Marshall Space Flight Center (MSFC)
- The Aerospace Corporation

Jointly funded by the NESC and NASA Science Mission Directorate (SMD).

Name	Discipline	Organization
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Jonay Campbell	Technical Editor	LaRC/KBR

Background

- **NASA was asked by the University of Central Florida (UCF), managing organization for the Arecibo Observatory, to support the investigation by providing:**
  - Subject matter expertise during efforts to restore facility after the 8/10/20 Auxiliary M4N socket/cable failure.
  - Forensic analysis, materials testing, and root cause analysis of the M4N socket/cable.
- **NASA Office of the Chief Engineer tasked the NESC with identifying any systemic risks to NASA assets or the broader engineering community.**
- **Collaborative effort between NASA, Aerospace Corporation, and Wiss, Janney, Elstner Associates, Inc. (WJE)**
- **Results were briefed to UCF/NSF and are published in a NASA report and NESC Technical Bulletin**
- **NASA did not have access to other observatory hardware for analysis and focused on the Aux M4N; additional hardware was requested for examination to further strengthen conclusions.**

Failure Analysis Activities

Category	Comments
Fishbone/Fault-tree Investigation	WJE provided significant data used in the disposition of NASA fishbones
Forensic Analysis/Reconstruction	NASA KSC led the forensic analysis with WJE collaboration/testing
Materials Testing	NASA KSC/MSFC characterized material properties that informed structural assessment
Socket Structural Assessment	NASA developed finite element models of as-built Aux M4N socket, performed sensitivity studies
Design Factors of Safety	NASA leveraged WJE expertise on the factors of safety used in civil engineering applications
Loads Model	WJE developed a loads model after failure that informed structural assessment
Expert Interviews	WJE/NASA jointly conducted expert interviews
Historical Knowledge	NASA leveraged WJE knowledge-base on the key events, facility designs, operation, inspections, etc.

Overview of Events

Tower 4 w/ M4N Socket

Aux M4N Failed Socket

Pulled-out wires/core

- **August 10, 2020:** Aux M4N cable on the north side of Tower 4 failed. Cable was a primary component of the system used to suspend the large, steel-framed platform (feed platform) above the telescope reflector dish.
- **November 6, 2020:** One of four original main cables of Tower 4 failed. Second cable failure was one of the original main cables, which had a different structural strand construction and cable termination.
- **December 1, 2020:** Second original main cable at Tower 4 failed, causing a chain reaction of failures and load imbalances in the suspension cable system that led to total collapse of the observatory.

NASA Assessment Process

Root Cause Analysis

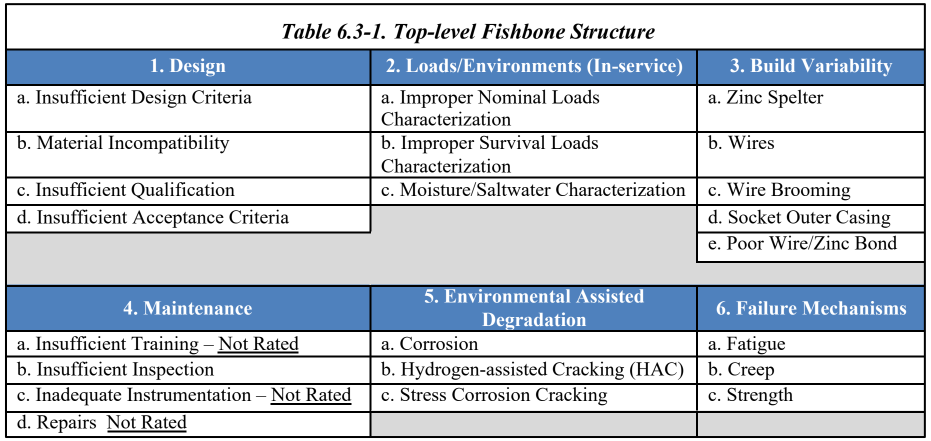
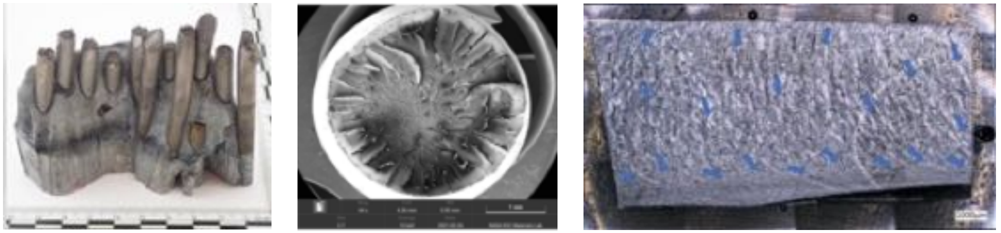


Table 6.3-1. Top-level Fishbone Structure

1. Design	2. Loads/Environments (In-service)	3. Build Variability
a. Insufficient Design Criteria	a. Improper Nominal Loads Characterization	a. Zinc Spelter
b. Material Incompatibility	b. Improper Survival Loads Characterization	b. Wires
c. Insufficient Qualification	c. Moisture/Saltwater Characterization	c. Wire Brooming
d. Insufficient Acceptance Criteria		d. Socket Outer Casing
		e. Poor Wire/Zinc Bond
4. Maintenance	**5. Environmental Assisted Degradation**	**6. Failure Mechanisms**
a. Insufficient Training – <u>Not Rated</u>	a. Corrosion	a. Fatigue
b. Insufficient Inspection	b. Hydrogen-assisted Cracking (HAC)	b. Creep
c. Inadequate Instrumentation – <u>Not Rated</u>	c. Stress Corrosion Cracking	c. Strength
d. Repairs <u>Not Rated</u>		

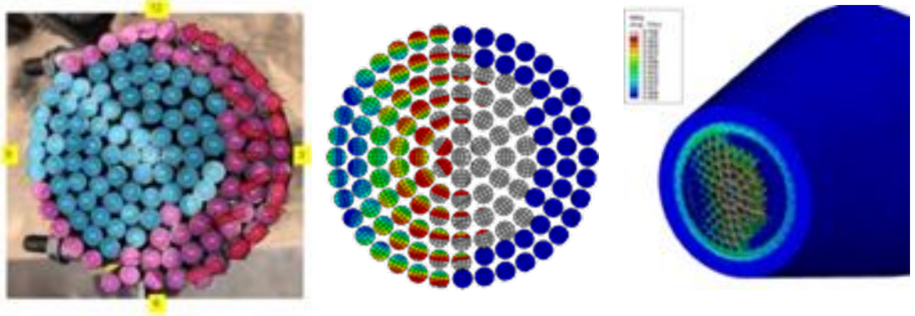
Forensic Analysis



Structural Analysis

- ✓ The NASA/Aerospace team employed a systematic failure analysis process that included forensic investigation, finite element modeling, and review of historical data
- ✓ NASA/WJE collaborated on socket/cable forensics, characterized material condition and failure mechanics.
- ✓ Structural analysis/sensitivity studies of potential factors performed in concert with forensics
- ✓ Root Cause Analysis weighed available data, most likely factors, and the failure progression.
- ✓ Developed findings and recommendations

Prediction of Failure Progression



Findings and Recommendations

Open Spelter Socket Mechanics

Background

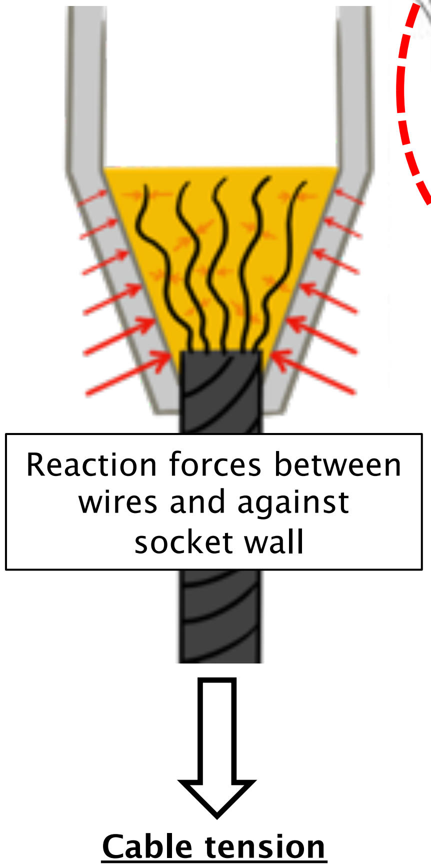
- Cables are structural hardware that transfer loads through tension and are widely used throughout industry in bridges, suspended objects, etc.
- Spelter sockets attach a termination fitting onto the end of a wire rope cable.
- The first failed cable, Aux M4N, was attached to Tower 4 using an “*open spelter socket.*”

Fabrication

1. Unraveling cable end to “fray” and fan out the individual wires (a.k.a. “brooming”).
2. Aligning the broomed cable end within the socket conical volume.
3. Pouring molten zinc or a hardening resin into the socket volume to surround and solidify/harden around the individual broomed wires.
4. Pulling on the cable to seat the solidified/cured material against the socket cone.

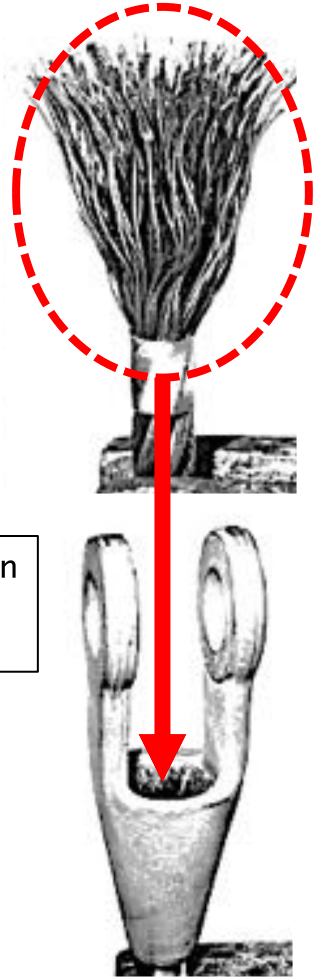
Critical Design Features

- Bonding between wires and the zinc enables transfer of cable tension to the zinc through shear loading.
- Brooming of wires allows zinc to embed between wires, causing a “finger-trap” effect of more compression on wires, further preventing wire pullout, aiding in load transfer.
- Socket conical angle provides wedging effect, prevents gross pull-through of material.
- Most critical region is the narrow side of the socket cone where compression is highest.
- Compression keeps the cable end intact in the socket and allows full cable strength to be developed outside the socket (wires/cable fail vs. slipping out from the socket).



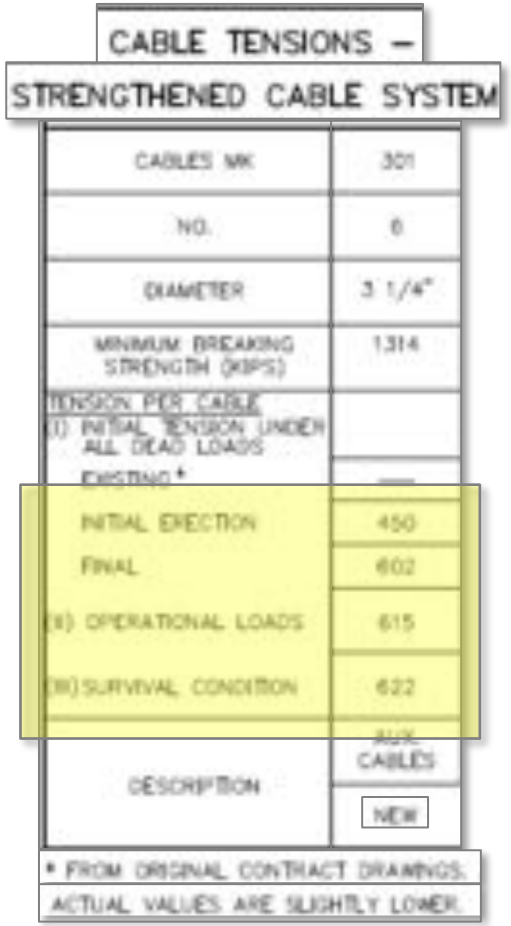
Reaction forces between wires and against socket wall

Cable tension



Loads

- **Observatory system loads model was employed by the designers to estimate loading distribution during erection, operation, and survival conditions.**
  - Erection loads considered dead load, modifications to feed platform, new Gregorian Dome: 602 kips.
  - Operational loads originally designated as erection loads + 50-mph wind at 90 °F: 615 kips.
  - Survival loads were originally designated as erection loads + 100-mph wind at 90 °F: 622 kips.
  - No additional live loads available to team for review; unclear whether any live loads were considered in design
- **WJE performed an independent loads assessment based on a variety of operational and survival conditions.**
  - Conditions correlated to sag measurements
  - Others were straight outputs from loads analysis.
- **WJE analysis indicated Aux M4N operational loading up to ~670 kips and survival loading up to ~720 kips, up to 15% higher than original design estimates. (See WJE Report)**



CABLE TENSIONS –
STRENGTHENED CABLE SYSTEM

CABLES MK	301
NO.	6
DIAMETER	3 1/4"
MINIMUM BREAKING STRENGTH (KIPS)	1314
TENSION PER CABLE (I) INITIAL TENSION UNDER ALL DEAD LOADS	
EXISTING *	----
INITIAL ERECTION	450
FINAL	602
(II) OPERATIONAL LOADS	615
(III) SURVIVAL CONDITION	622
DESCRIPTION	AUX CABLES NEW

* FROM ORIGINAL CONTRACT DRAWINGS. ACTUAL VALUES ARE SLIGHTLY LOWER.

Operation	
Azimuth (deg)	M4N (kips)
0	667.8
30	661.3
60	639.5
90	622.5
120	607.0
150	603.1
180	608.8
210	618.4
240	632.1
270	641.9
300	640.6
330	660.8
Min	603.1
Max	667.8
Mean	633.7
Diff	64.7
% of mean	10.21%

Survival	
Wind Direction	M4N (kips)
S	684.7
SE	716.2
NE	649.8
N	557.3
NW	522.9
SW	590.9
Min	522.9
Max	716.2
Mean	620.3
Diff	193.3
% of mean	31.16%

Industry Standards/Guidance

- **Standards and guidance in the Aux M4N design are unknown but required a minimum 2.0 factor of safety and 50% proof load per WJE.**

- **ASCE 19-10, *Structural Applications of Steel Cables for Buildings,* is a civil engineering standard reviewed and compared against Aux M4N:**
  - Requires a minimum of 2.2 for steel cables.
  - Section 3.1.1: *cable system structures should be configured to maximize structural redundancy and that failure or malfunction of any one local component should not result in structural collapse.*

- **Reference 21 recommends a factors of safety > 2.2 for sufficient redundancy in cable-stayed bridges (shown right).**

- **AASHTO Moveable Bridge Specification recommends safety factors between 4.0 and 8.0 depending on cable function, U.S. Dept. of Interior Bureau of Reclamation suggests 5.0 for hoisting cables & wire ropes.**

- **Crosby uses ~5.0 for the design of the socket itself.**

Standards	Design Factor of Safety for Stay cables of CSBs
Japan Road Association. Specifications for highway bridges: part II, steel bridges. Tokyo: Japan Road Association; 2017. Japanese.	2.5
EN 1993-1-11: Eurocode—3. Design of steel structures—Part 1–11: Design of structures with tension components. European standard. Brussels: European Committee for Standardization; 2006.	2.2
Post-Tensioning Institute. Recommendations for stay cable design, testing and installation. 5th ed. Farmington Hills: Post-Tensioning Institute; 2007.	2.22
Service d'Etudes Techniques des Routes et Autoroutes. Cable stays—recommendations of French interministerial commission on prestressing. Bagneux Cedex: Service d'Etudes Techniques des Routes et Autoroutes; 2001. French.	2.174
International Federation for Structural Concrete. Acceptance of stay cable systems using prestressing steels. Report. Lausanne: International Federation for Structural Concrete; 2005.	2.2

21. K. Ali, H. Katsuchi, H. Yamada, "Comparative Study on Structural Redundancy of Cable-Stayed and Extradosed Bridges Through Safety Assessment of Their Stay Cables," Engineering, Volume 7, Issue 1, January 2021, Pages 111-123

Industry standards/guidance recommend a design factor of safety > 2.0

Industry Standards/Guidance (cont.)

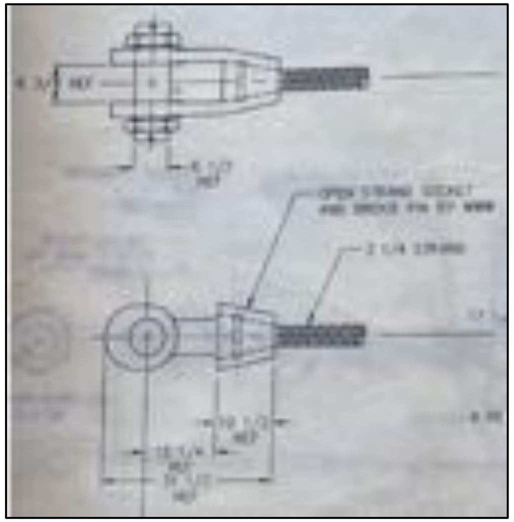
- **Civil engineering designers typically select termination type and associated structural strand from catalog values provided by hardware suppliers (such as Bethlehem Steel).**
  - Correspondence with subject matter experts indicated that design verification for sockets like the Aux M4N used a ‘pull test to failure’ for showing compliance against a rated breaking strength requirement.
  - No additional design/build verification-type tests are known by this team to have been performed for creep, fatigue, corrosion resistance, or build defect acceptance.
- **Review did not identify civil engineering standards such as ASCE 19-10 that explicitly account for the dead/live ratio in defining the service life interval.**

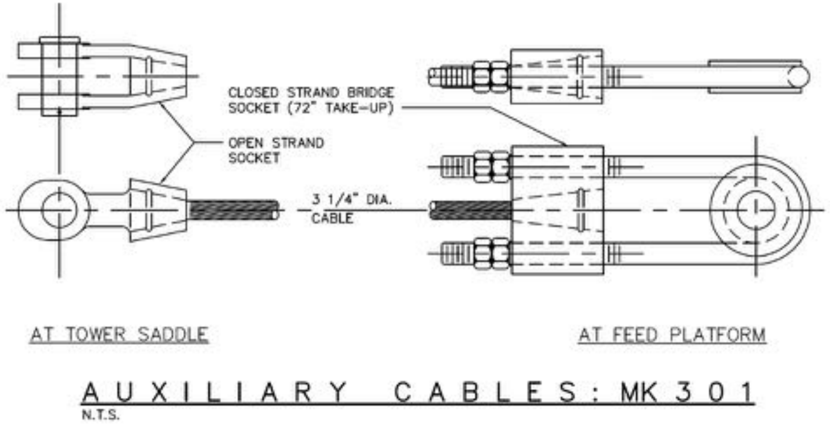
Load Ratios

- Factors of safety calculated with WJE predicted survival loads: $\frac{1{,}314}{720} kips = 1.83$ < 2.0 (recommended)
- Target proof-test loads of socket termination specified as 50% of rated breaking strength, 657 kips
- Actual minimum proof factor: $\frac{657}{720} \, kips = 0.91$ < 1.0 (recommended)
- Dead load percentage of total load (range):
  - $Max = \frac{670}{720} kips = 93\%$
  - $Min = \frac{603}{720} kips = 84\%$

Dead load is a significant percentage of total design load, Greater significantly than literature search of bridge applications (~40–60%)

Design Criteria /Verification





Description	Industry Guidance/Target	Actual Aux M4N	Conservative
Factor of Safety	> 2.0	< 2.0	No
Proof test factor	> 1.0	< 1.0	No
Loads Predictions	515/622 kips (oper./surv.)	Up to 15% higher	No
Deadload %	40-60% typical	84-93%	No standard

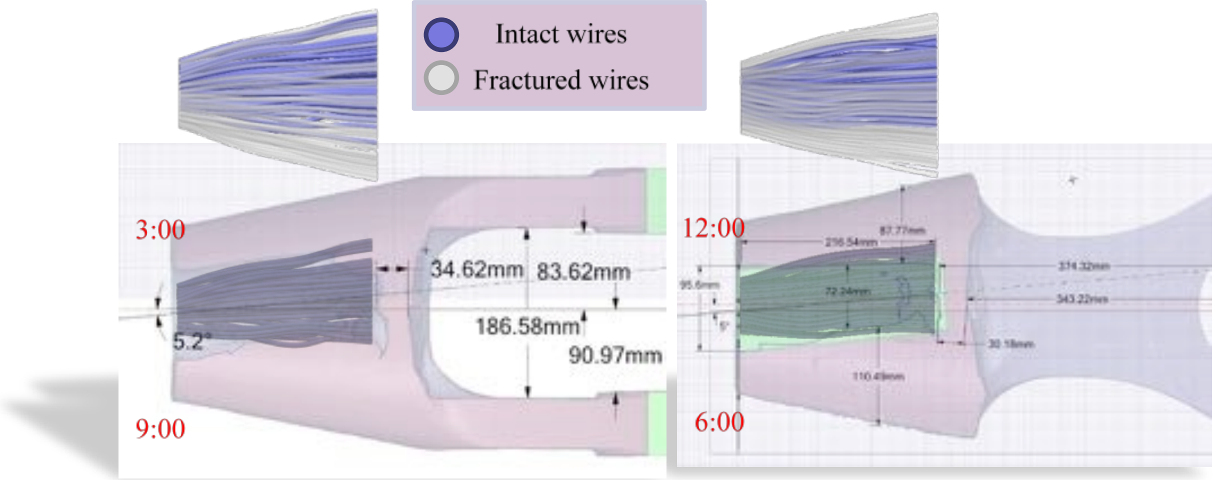
Structural strand construction was 3.25-inches in diameter 1×127 with rated breaking strength of 1,314 kips (A586-91), 160 ksi YS, 220 ksi UTS

Design and build verification methodology for the Aux M4N design was unconservative with respect to current industry standards

Forensic Investigation

- **NASA and WJE collaborated on a forensics plan of the socket and cable ends.**
- **Examination characterized both the material condition and failure mechanics.**

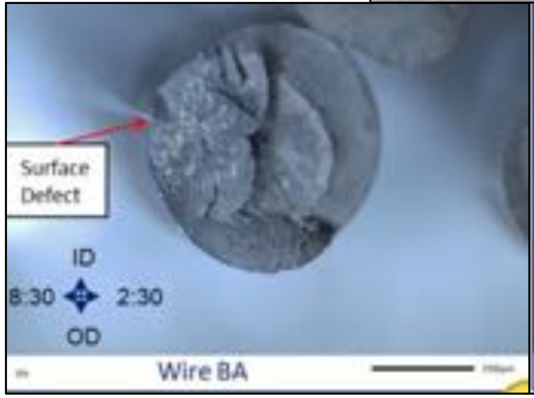
- **Nondestructive examination**
  - Visual inspection
  - Chemical analysis
  - Radiography, magnetic particle inspection
  - Metrology
  - Three-dimensional (3D) laser scanning
- **Destructive examination**
  - Visual examination
  - Wire mapping/reconstruction
  - Fractography
  - Metallography
  - Mechanical testing

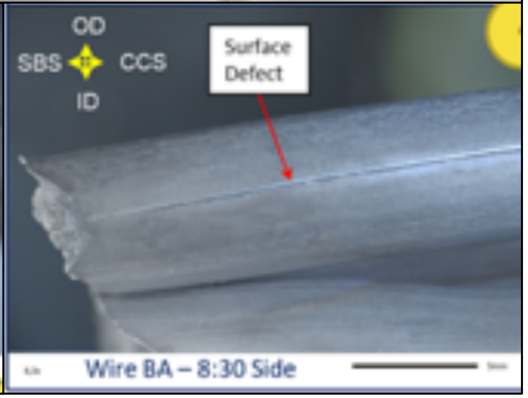


Fabrication Process and Defects

- **As-received socket housing and cable met spec/reqt's, but contained some defects analyzed for potential contribution:**
  - Zinc porosity
  - Solidification gas bubbles near the casting cap surface
  - Poor wire/zinc bonding at the wire ends
  - Brittle fracture region
  - Cracks throughout the bulk zinc
  - Five of 126 wires had surface defects in vicinity of fracture:
    - At least two were influential in their fracture; one of two probably HAC.
  - Three of 126 wires found to be mixed-mode fractures, in part HAC.
  - FEM evaluated the effects of voids/defects (discussed later)

- Most features inconsequential to failure progression (more discussion to follow)
- Surface defects on a few outer wires may have contributed to wire failure initiation and progression



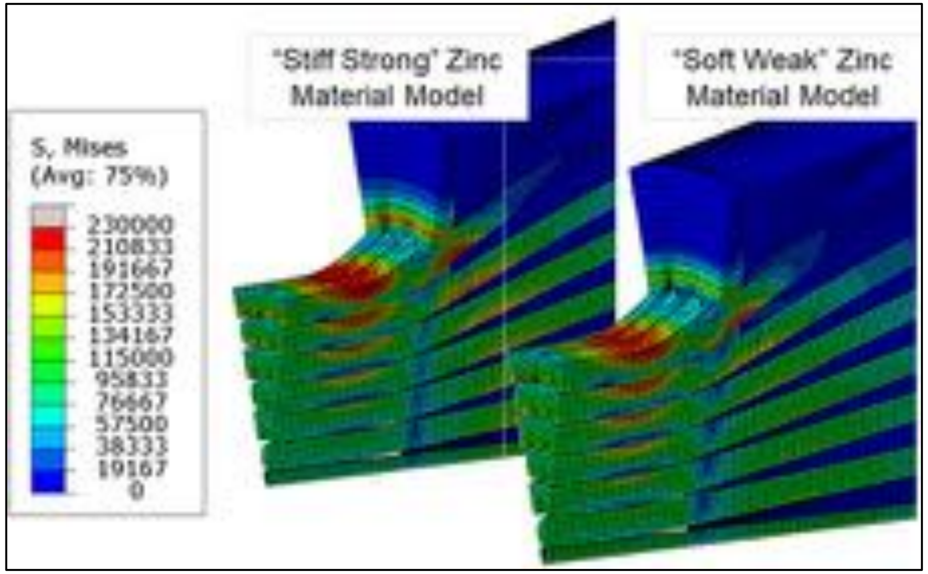


Corrosion

- **Moisture pathways caused corrosion throughout the socket**
  - Mastic coating cracks, between the socket inner wall and the zinc outer wall, along wires protruding through the zinc outer wall, along cracks in the zinc, and along other wires.
- **Steel + zinc -> galvanic coupling -> accelerated amount of zinc oxide, uncoupling caused trace iron oxide.**
  - Worst between the steel socket and zinc casting, upper two-thirds.
  - Next worst was along the wire ends, notably at the wire imprint region.
  - Then along some wires near their fractured ends.
  - Least was between the steel socket and zinc casting, in the lower third.
- **Where no steel present, zinc oxide product found in varying quantities.**
  - Worst was in the gas bubbles near the casting cap.
  - Next was along cracks in the bulk of the zinc casting.
  - Then along ridges in the brittle fracture region.
  - Least was over the exposed zinc surfaces in the cavity a few inches away from the rear of the cavity (wire channels) and over faceted regions of the brittle fracture region.

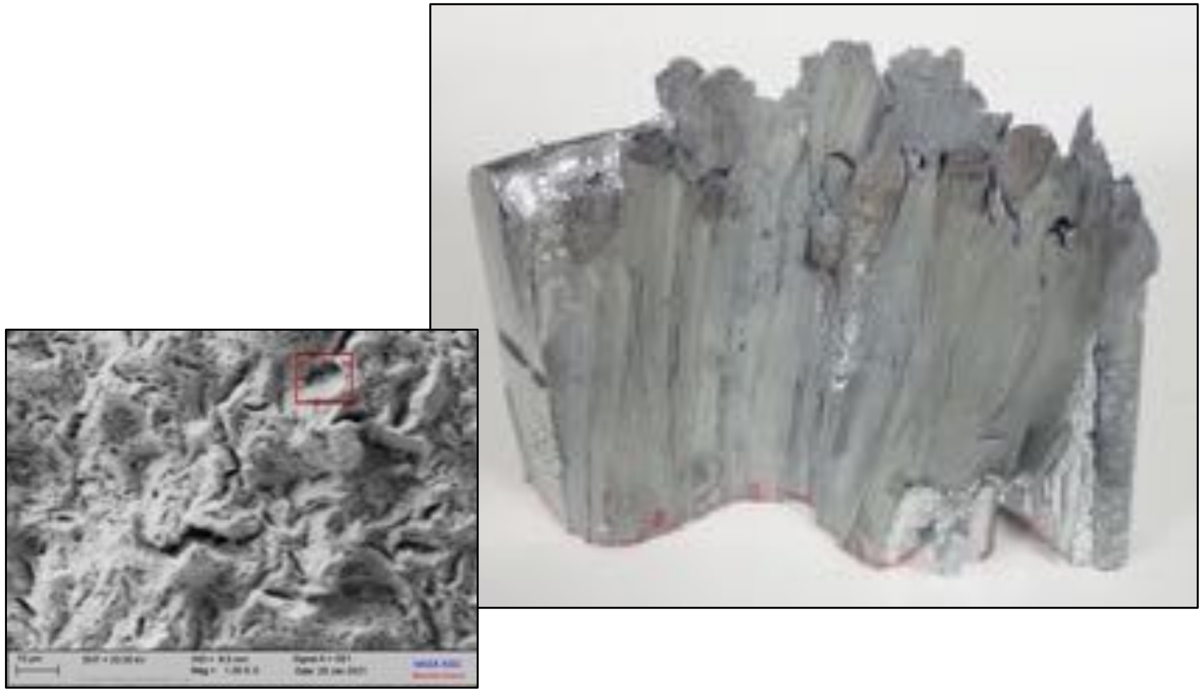
Corrosion (cont.)

- **Analysis of contribution to socket failure:**
  - Percent metal loss to the overall zinc and steel structure was negligible.
  - No appreciable difference to wire/zinc bond strength from corrosion along wires.
  - Minimal effects on wire stresses based on a finite element model sensitivity study of varying conditions between the socket housing and the zinc.
  - Negligible effects on maximum predicted wire stress due to voids/defects near the casting cap.



Galvanically Revealed Fracture Surface

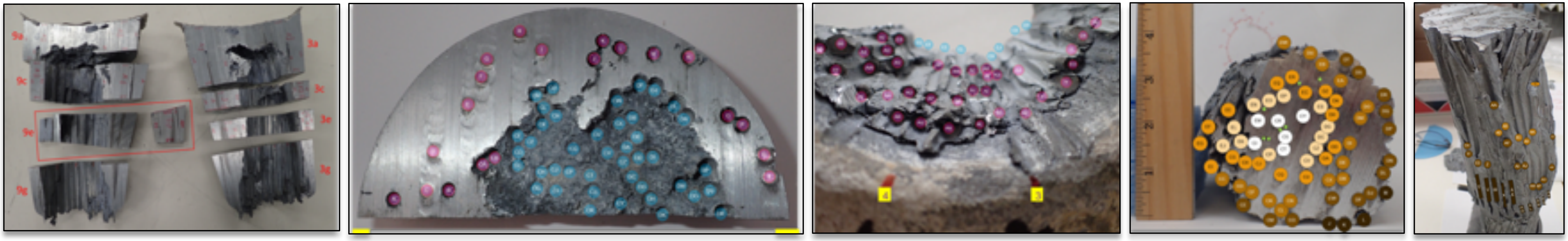
Before



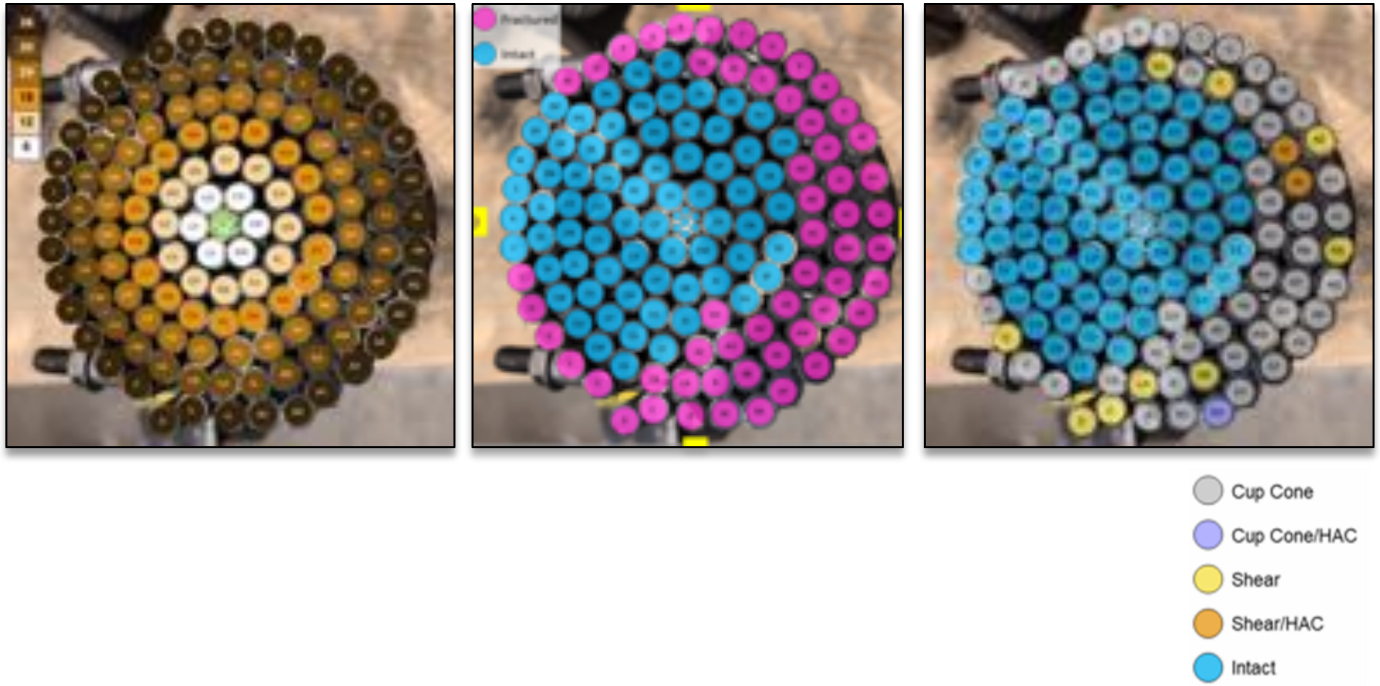
After

- **Fracture surfaces were revealed by immersing sections of the socket base slice into hydrochloric acid**
  - Galvanic reaction corroded the zinc metal, while protecting the steel wires; no effects observed to 1000x
  - Enabled wire fractures to be visualized together, in their socket positions.
  - Process did not retain corrosion evidence on wire fracture surfaces.

Wire Mapping

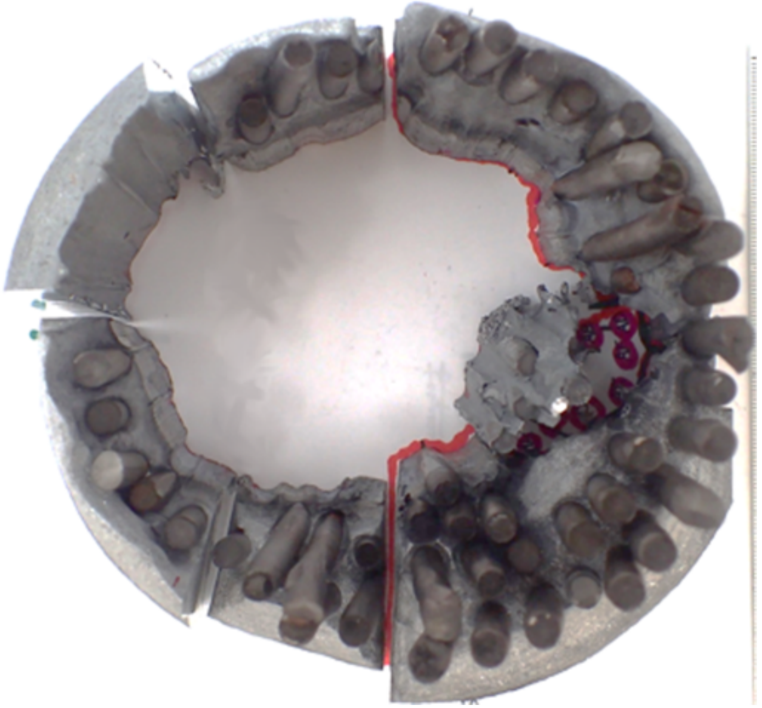


- Zinc casting was sectioned from the casting cap to the socket base opening
- Wires labeled/tracked through the process
- Wires matched with their mating halves from the cable/zinc slug
- Final mapping aided in creating an as-built analytical model and understanding of the failure from a “system of wires” point of view

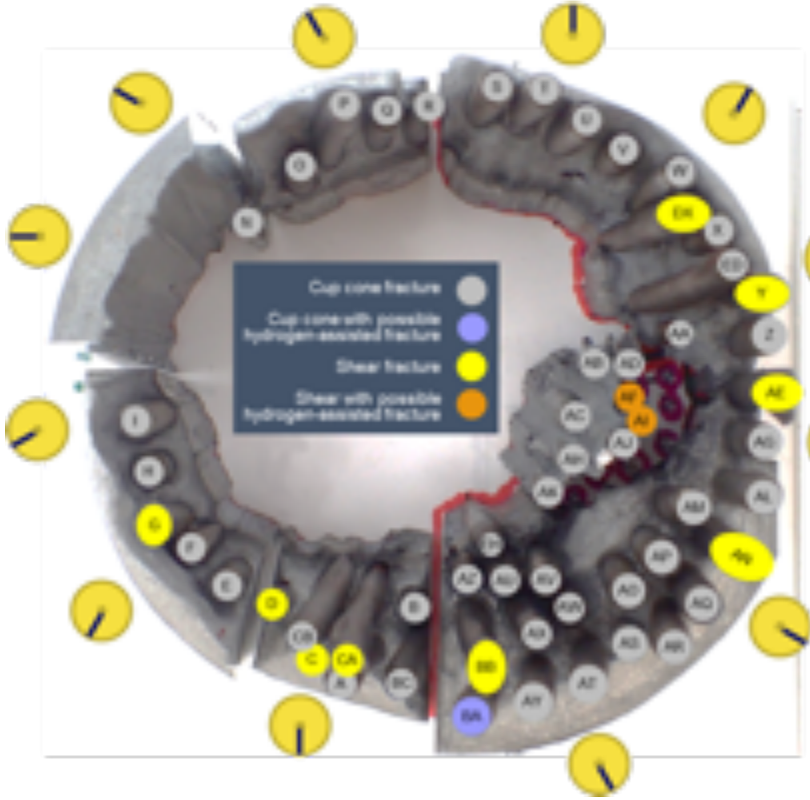


Wire Mapping (cont.)

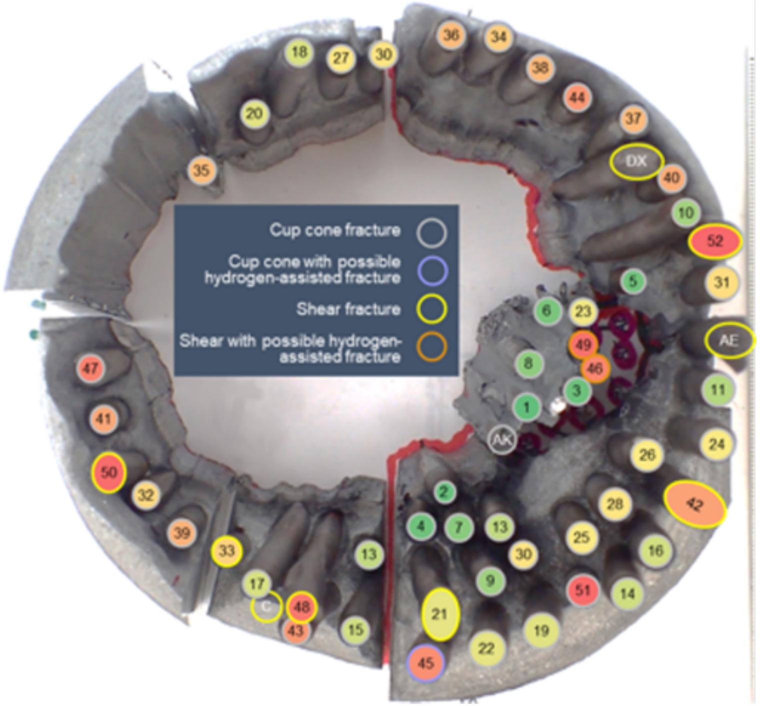
Visual Model



Fracture Classification



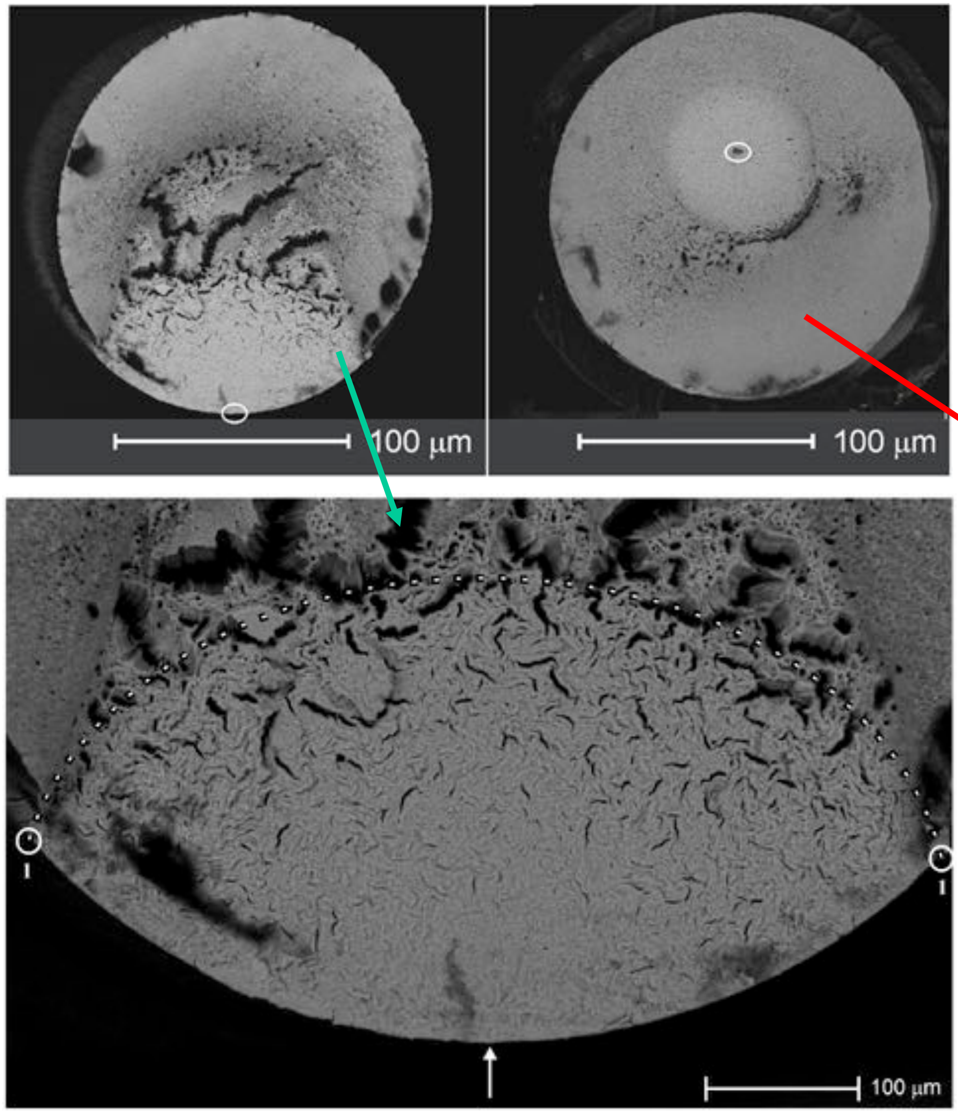
Relative Necking
(green is most; red is least)



Cold-Drawn Pearlitic Steel Wire Reference Examples

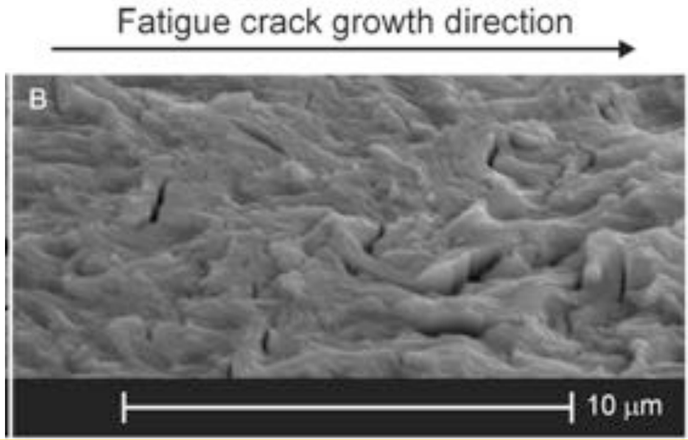
Surface Initiated Fatigue Crack

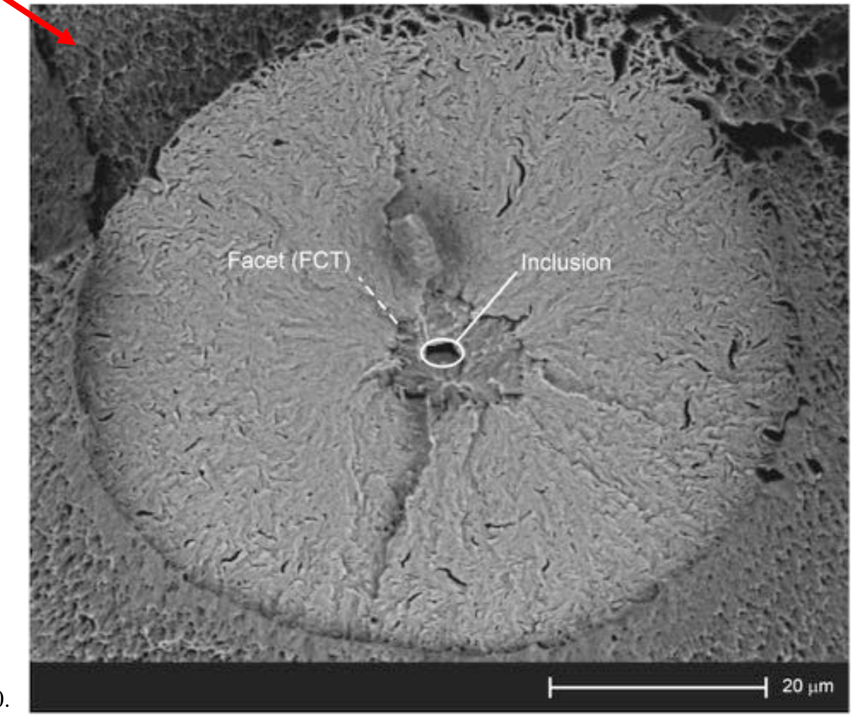
Inclusion Initiated Fatigue Crack



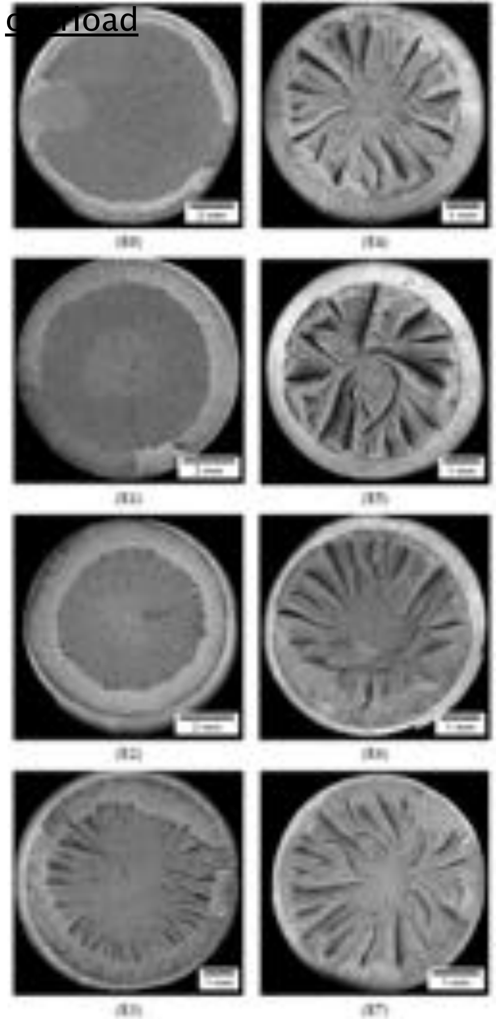
Lambrighs, K., "Fatigue Properties of Heavily Drawn Steel Wires," November 2010, ISBN 978-94-6018-273-0.

Oblique Surface View





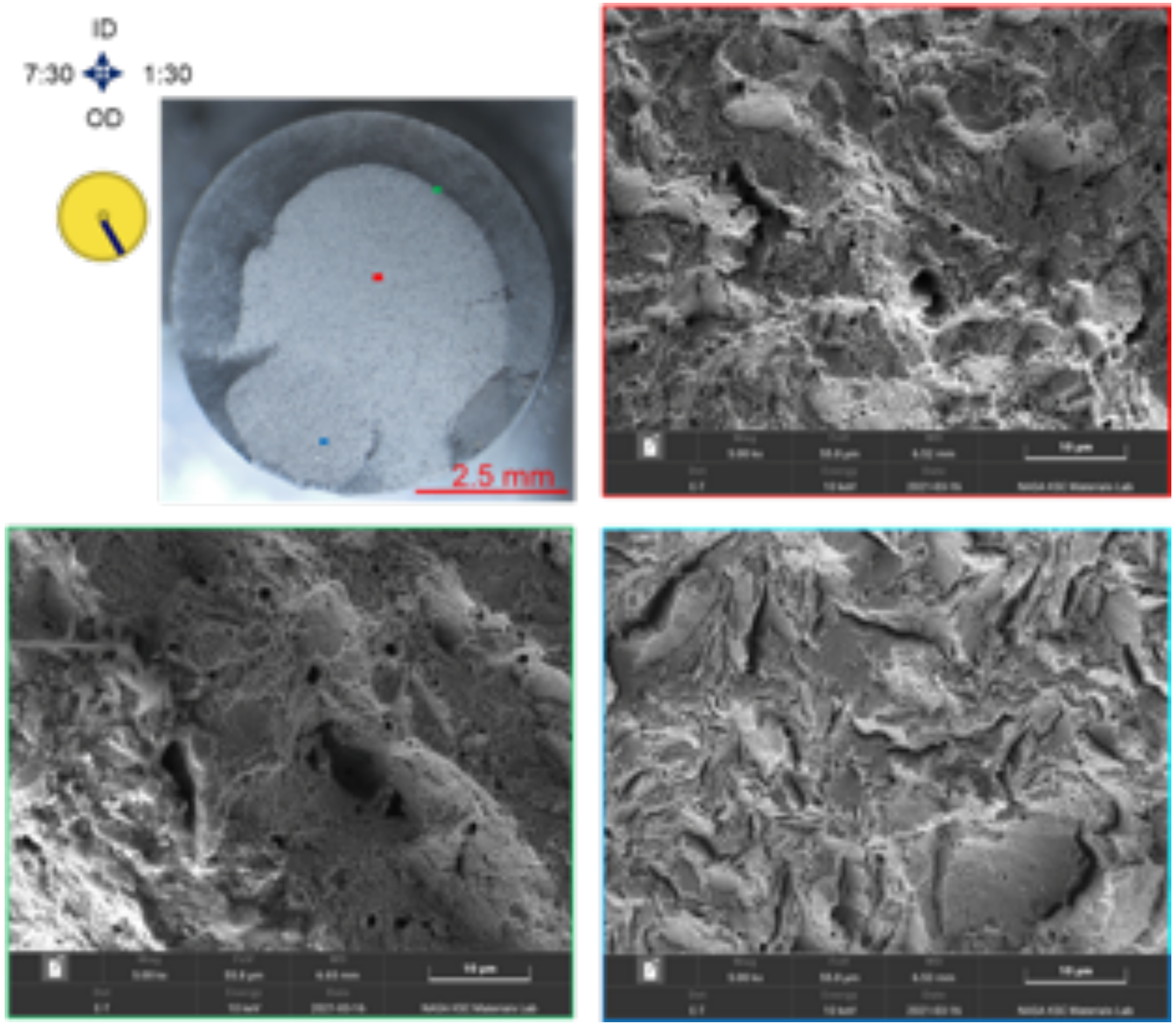
Gradually more progressively cold-drawn pearlitic steel wire specimens failed by tensile overload



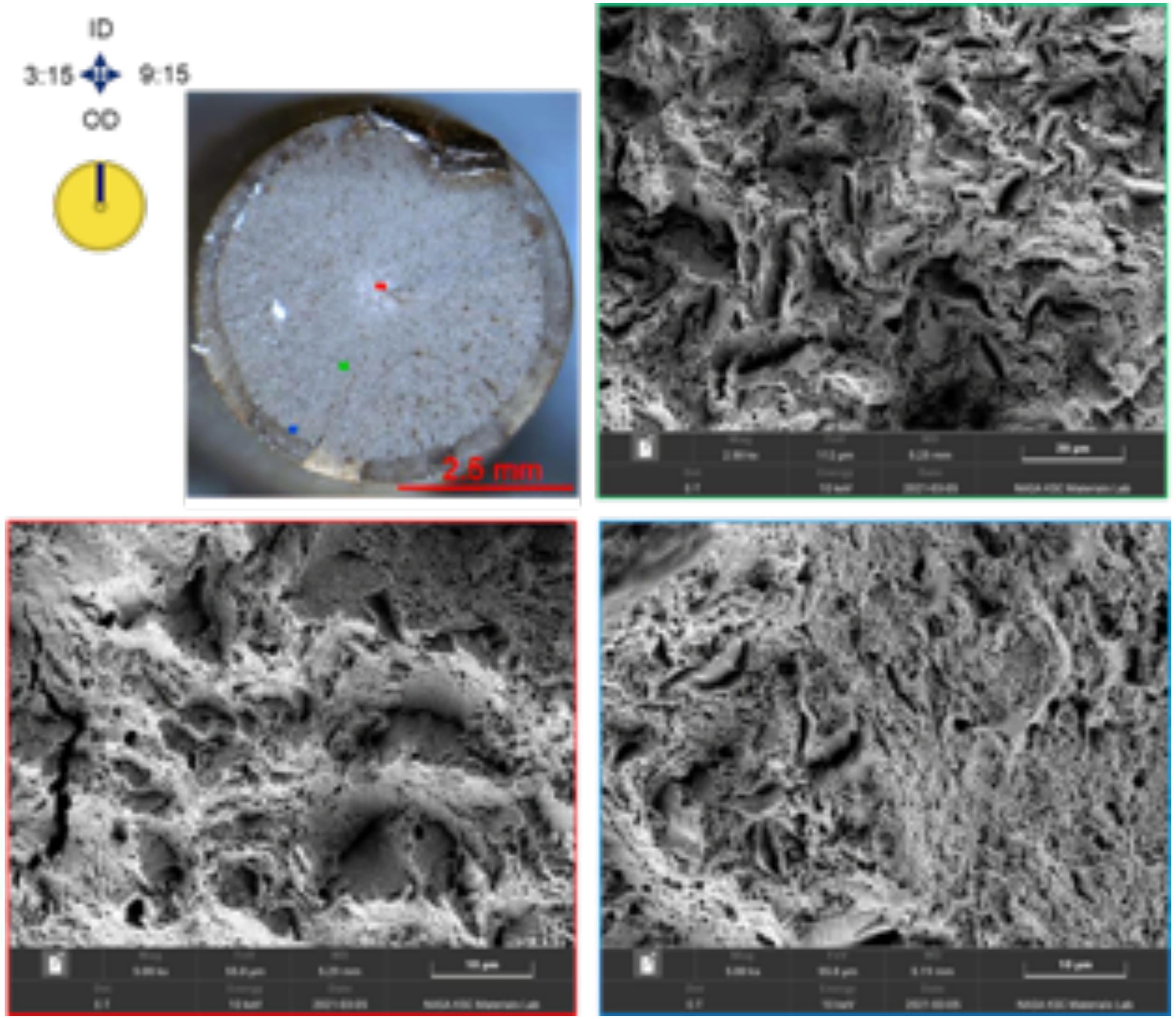
Toribio, J., et al., "Tensile Fracture Behavior of Progressively Drawn Pearlitic Steels," *Metals*, Vol. 6, No. 5, p. 114.

Cold-Drawn Pearlitic Steel Wire (cont.)

Wire AS

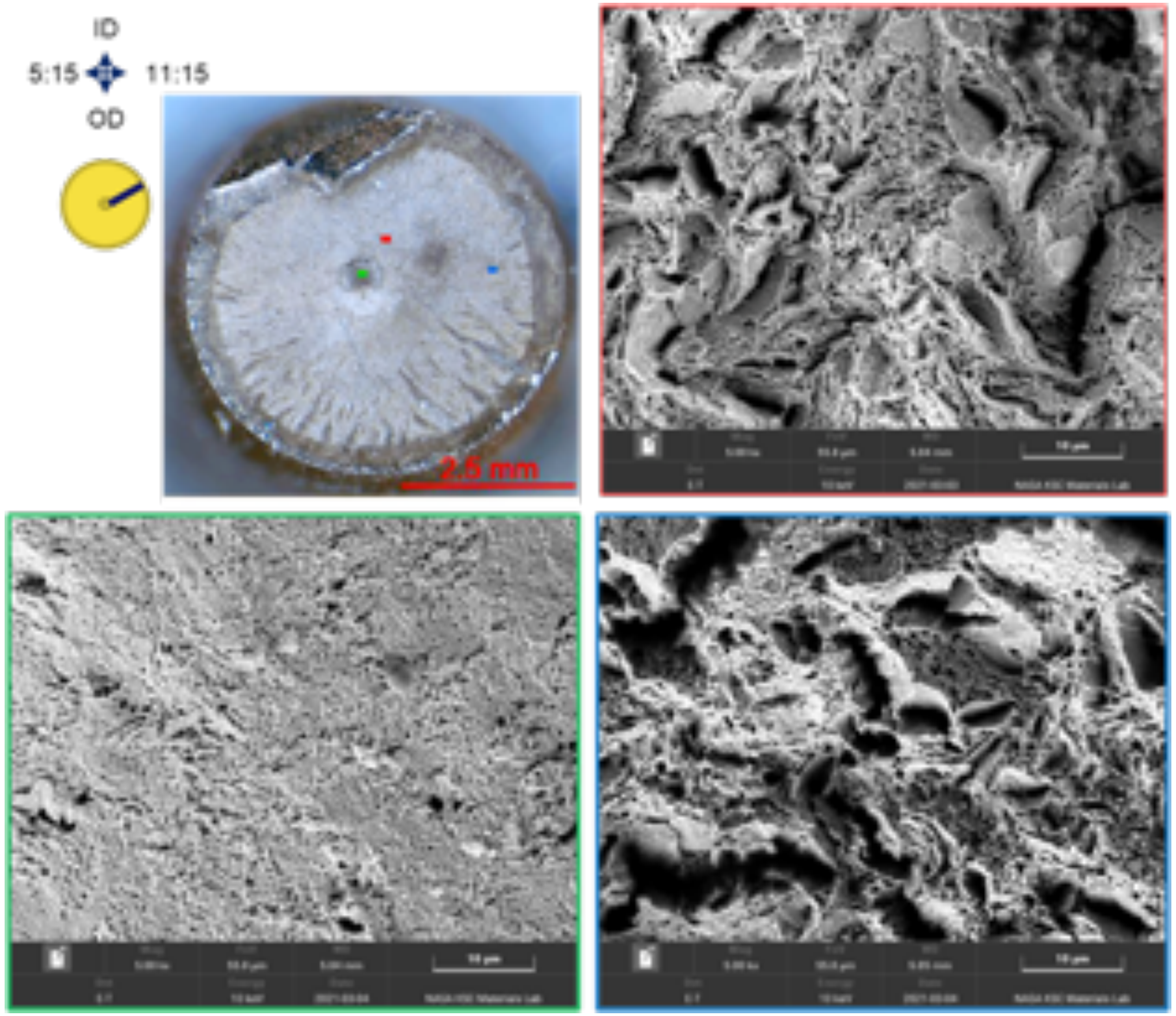


Wire U

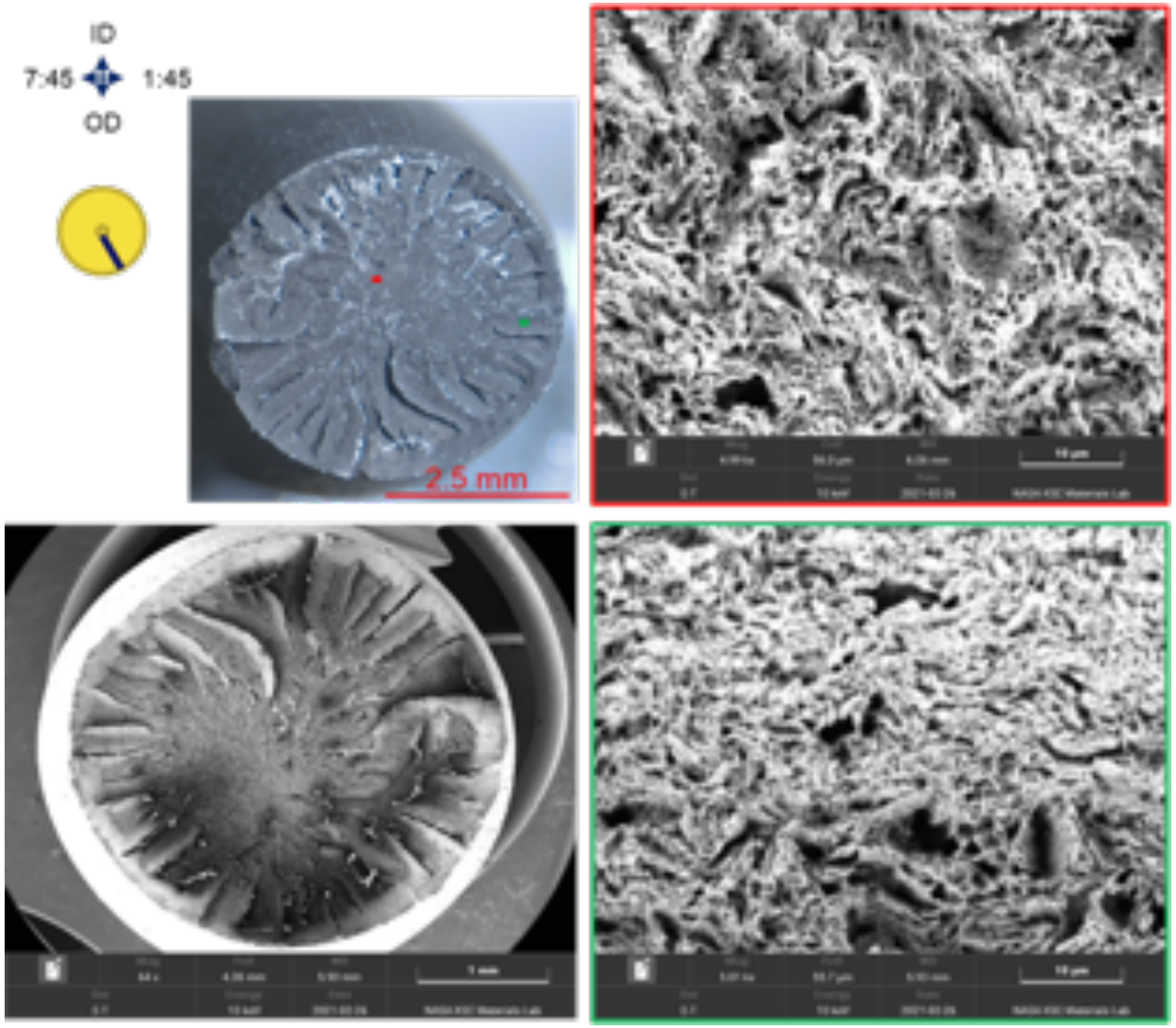


Cold-Drawn Pearlitic Steel Wire (cont.)

Wire Z



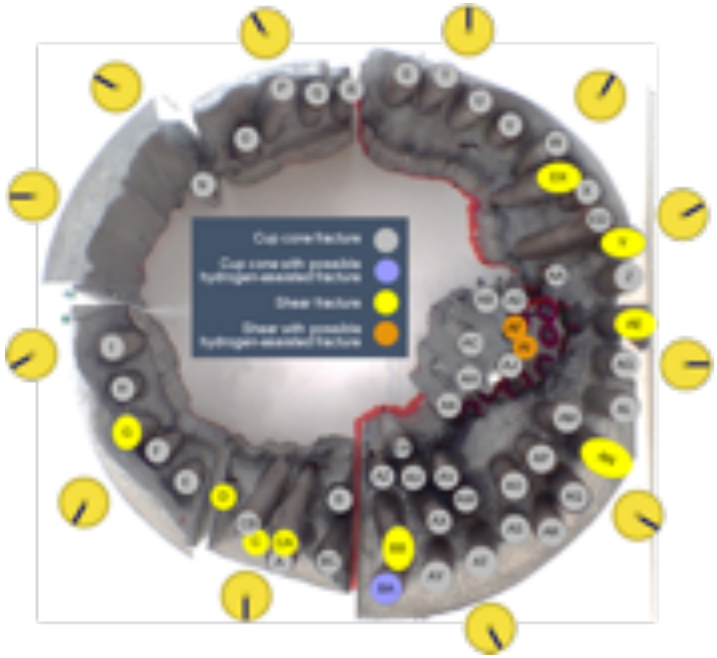
Wire EH

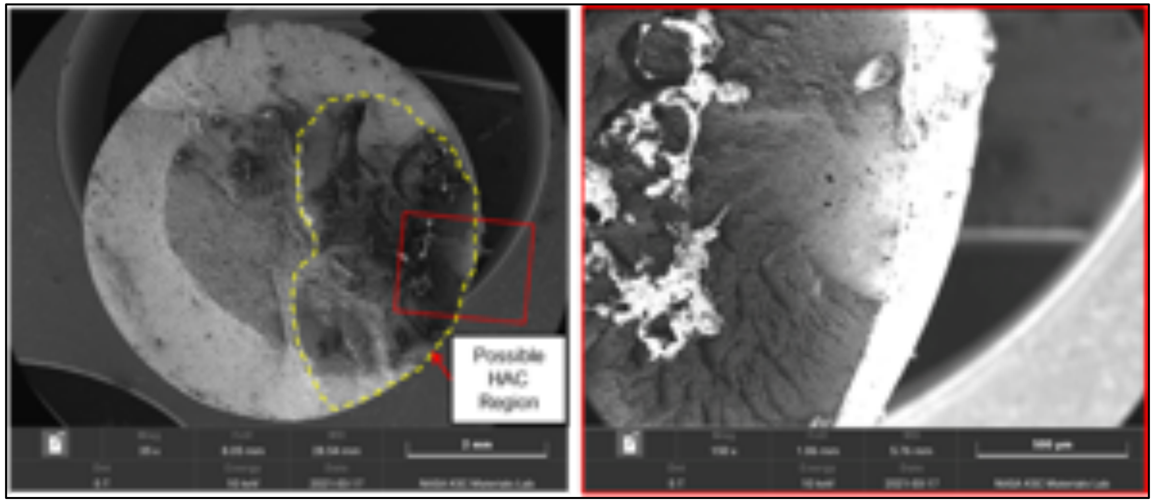


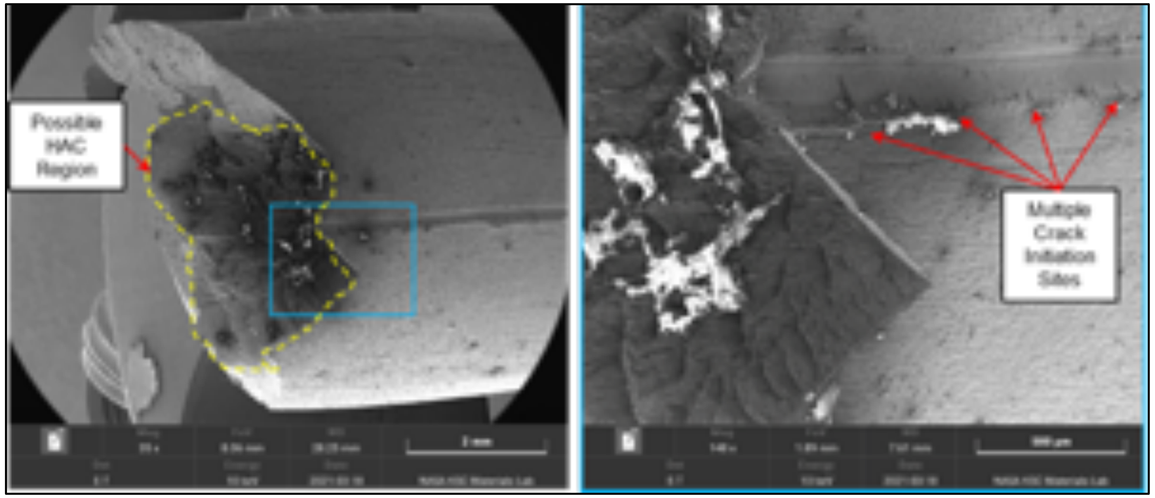
Hydrogen-assisted Cracking

HAC is caused by diffused hydrogen accumulating at stress concentrations and further decreasing strength capacity of the wires, which can lead to wire cracking.

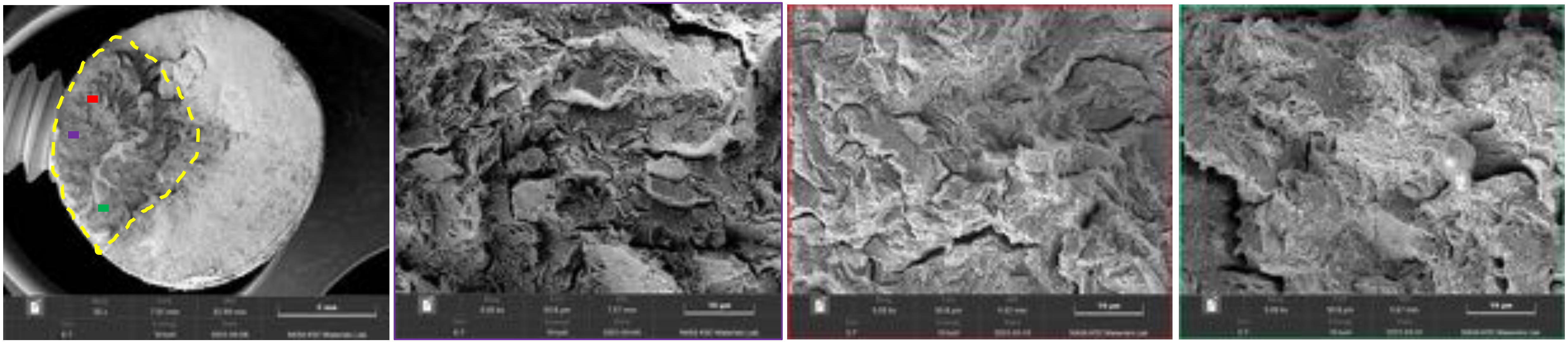
- HAC can accelerate failure, especially when subject to sustained loading, and has negative structural margins over the entire service life.
- Three wires exhibited mixed-mode fractures, with one mode being progressive failure, probably HAC.



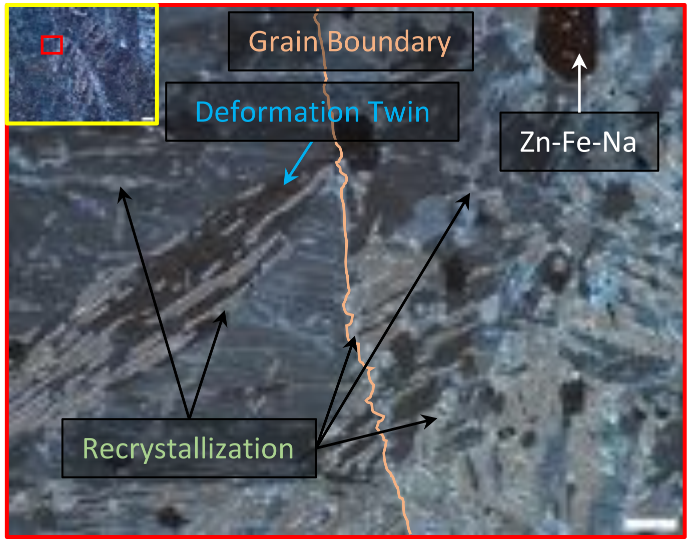




Cyclic Loading / Fatigue



- **Forensic analysis found no clear attributable evidence of fatigue cracking:**
  - No clear evidence of fatigue in the zinc (e.g., transgranular deformation in the zinc grains); lesser possible contributions from cyclic loading is not discernable from the overall contributions of damage due to sustained loading.
  - No evidence of beach marks, striations, or classic fracture characteristics of fatigue in cold-drawn pearlitic steel wire in 53 cup-cone and shear fractures.
  - The only wire fractures with potential cyclic loading contribution were the three HAC wires; mixed-mode, with either shear (2) or cup-cone (1).



Creep

> *"Creep is the tendency of a solid material to move slowly or deform permanently as a result of long-term exposure to persistent high mechanical stresses that are still below the material yield strength." – "Creep (deformation)," Wikipedia.*

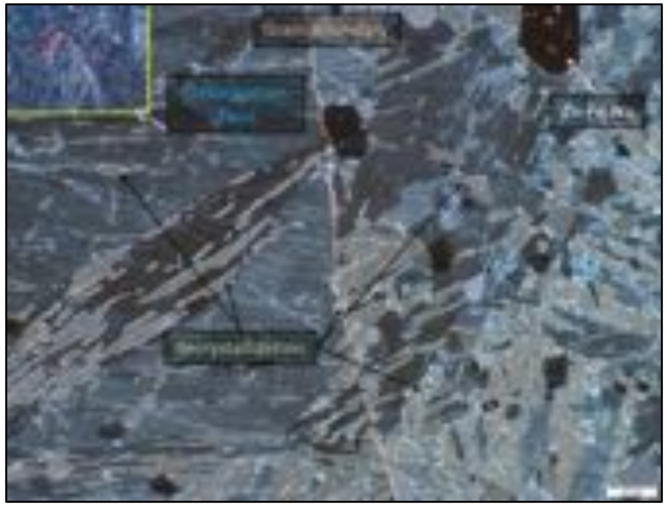
- In stressed polycrystalline metals, creep is generally classified as a high temperature process, activating creep deformation mechanisms at homologous temps (T_H) ≥ 40%
- Commercially pure zinc has a melting point of (420°C = 788°F = 693K), ~42% of its melting point at room temperature (20°C = 68°F = 293K).

$$\boxed{T_H = \frac{T(K)}{T_{mp}(K)} = \frac{293K}{693K} = 0.42}$$

- Recrystallized grain boundaries generally oriented 45° to the stress direction have been associated in literature with pure zinc creep at low zinc-creep temperatures.*

Recrystallization is evident within the zinc grains:

- Between the socket and cable section:
  - Adjacent to the zinc failure, grains are fully recrystallized.
  - Closer to the socket, the zinc grains were also recrystallizing.
  - Wide dispersion of recrystallization suggests that recrystallization was not due to heat dissipation from the core pullout failure event.
- Intermittent, non-connected cracks were found in the fully recrystallized region, which appear to be predominantly intergranular; if related to creep, cracks suggest that creep failure was a slow process.



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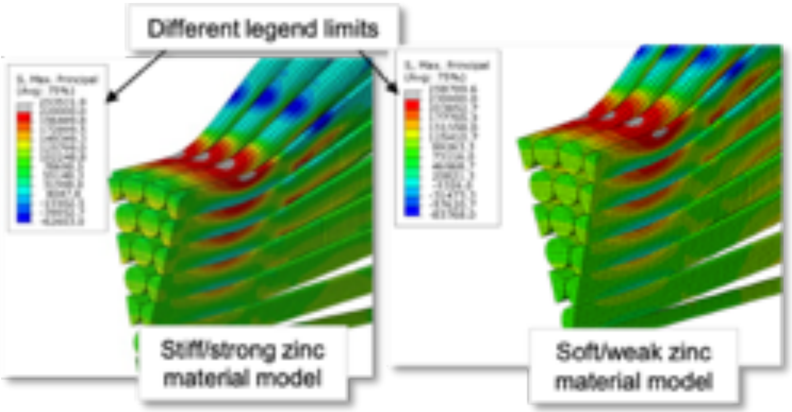
*Singh et al. "On the Role of Grain-Boundary Migration during the Creep of Zinc," *Journal of Materials Science,* Vol. 8, 1973, pp. 373-381.

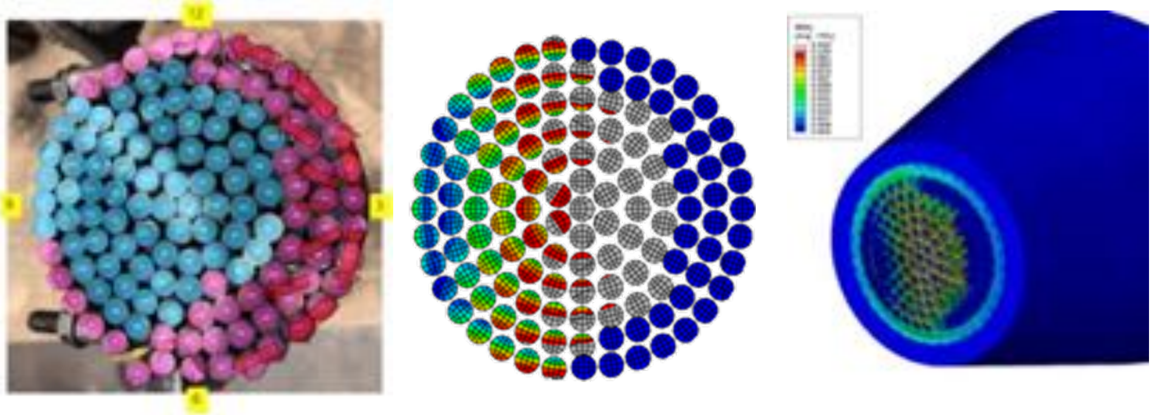
Structural Analysis

- Structural analysis was performed by The Aerospace Corporation in concert with other investigation elements.
- Models developed to understand socket load transfer mechanics and perform sensitivity studies on parameters including brooming, material properties, and voids.
- Assessed credibility of potential factors and informed understanding of the likely failure progression.

Aux M4N Wire Reconstruction



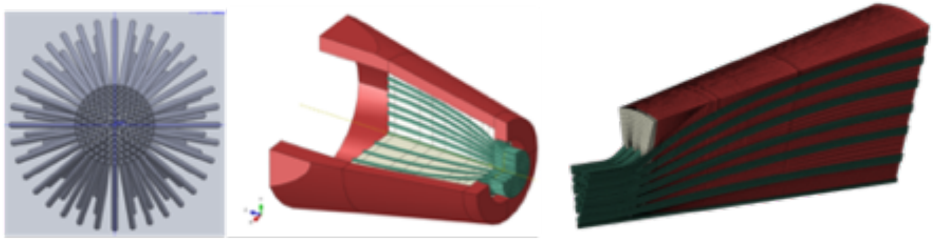
Sensitivity Studies

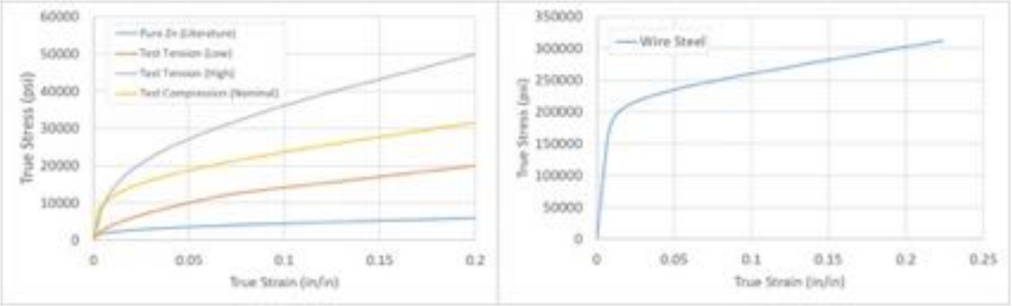


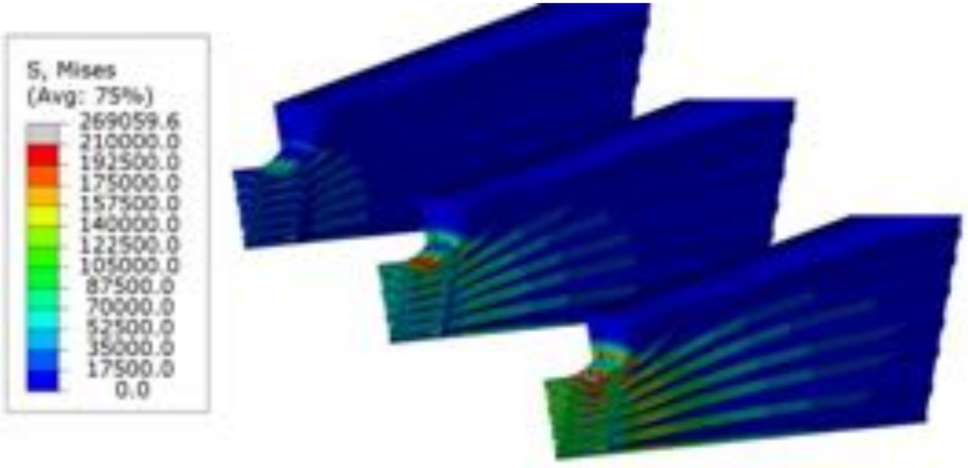
Prediction of Failure Progression

Structural Analysis Overview

- **Multiple Abaqus/CAE model configurations:**
  - Brooming configurations (full, partial, poor, as-built).
  - Fully circumferential 3D models.
  - 30-degree wedge 3D models.
  - Variety of material property, contact interactions, voids, progressive damage, loading variability, etc.
- **Major conclusions:**
  - Stress concentrator exists at wire outlet of socket due to geometric factor of broomed wires, interaction with socket, load distribution of zinc, and other factors.
  - Outer wires were stressed beyond yield during proof-testing operation, and potentially during operation.
  - Load redistributes to radially inward as joint sees further increasing loads.
  - Outer wire stress is high regardless of zinc material model, brooming configuration, and other parameters.
  - Zinc creep leads to further stress increases in already highly loaded outer wires.

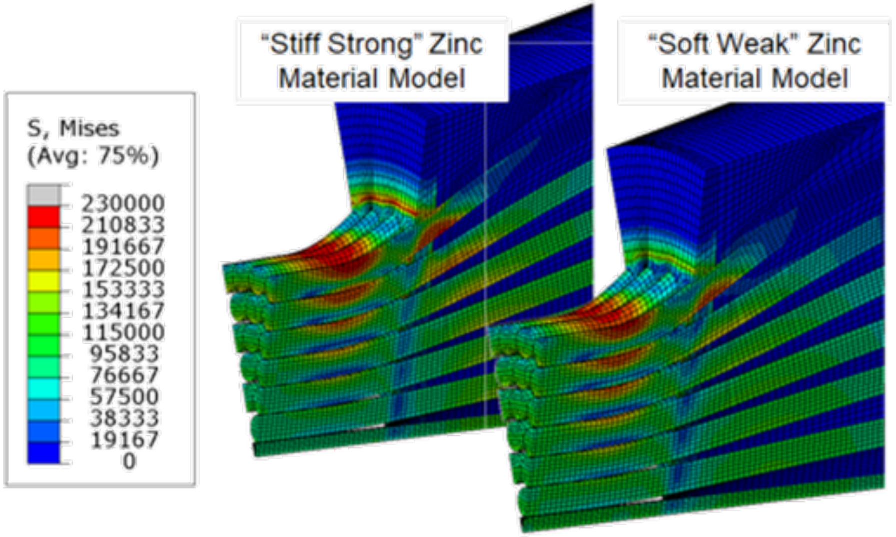






Structural Analysis Overview (cont.)

- **Despite a ~2.0 design factor of safety on cable rated breaking strength, the constituent stress margins for wire under operational load (~600 kips) were much lower:**
  - Wire strength range: 220 ksi to 250 ksi.
  - Outer wire stress range: 220 ksi to 230 ksi.
  - With FS = 1.0, margins of safety: $MS_{low} = \frac{220\ ksi}{1.0*230\ ksi} - 1 = -4.3\%$
  - With FS = 2.0, margins of safety: $MS_{low} = \frac{220\ ksi}{2.0*230\ ksi} - 1 = -52.2\%$
- **Key question: How did the design tolerate >1,300 kips when outer wire stresses were so high at operational loads?**
  - Rated breaking strength is determined by loading a cable until net section failure. Total cable overload does not occur until most of the individual wires are yielding and collectively reaching their ultimate elongation limit (~5% strain).
  - At 600 kips, the outer wires begin to plastically deform, but the full cable cross section continues to develop load-bearing capability as load redistributes radially inward.



Net section area: $A_t = \frac{n\pi d^2}{4} = \frac{127\pi(0.25^2)}{4} = 6.234\ in^2$

Net section stress at operation: $\frac{F}{A_t} = \frac{600{,}000}{6.234} = 96.25\ ksi$

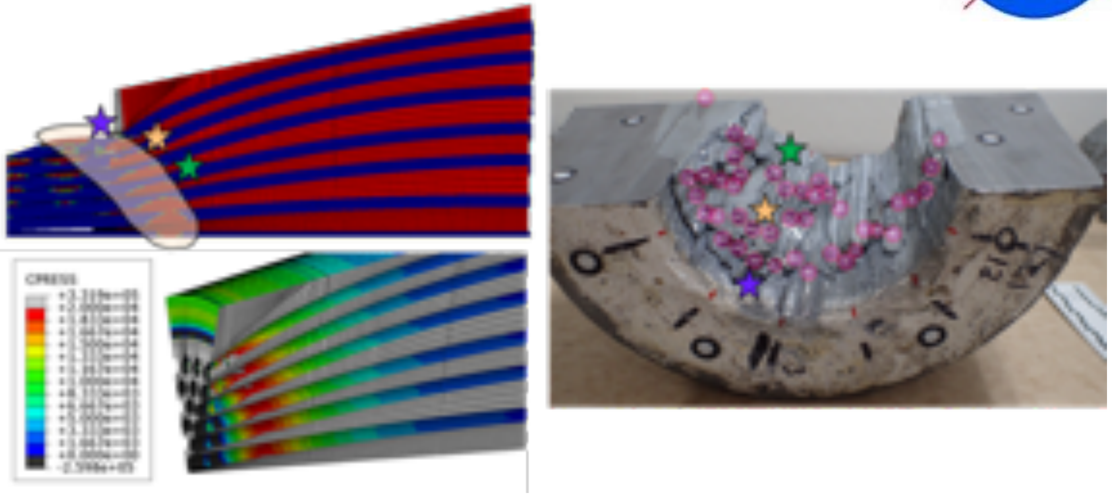
Consider individual wire strength of 220 ksi:

Net section stress at failure: $\frac{F}{A_t} = \frac{1{,}314{,}000}{6.234} = 210.8\ ksi$

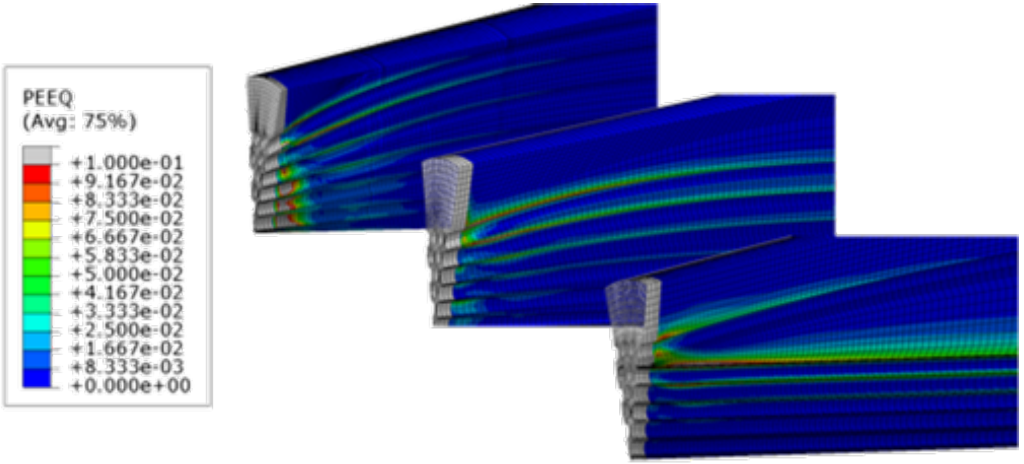
Basic hand-calculations verify gross capability expectation of cable breaking strength despite local stress peaking at lower loads.

Structural Analysis Overview (cont.)

- **Finite element analysis informed the understanding of overall socket mechanics and sensitivities.**
- **Desired socket performance is heavily influenced by the following characteristics:**
    - Conical shape of socket internals.
    - “Seating” of zinc slug within socket due to friction and plastic flow.
    - Proper wire brooming for load transfer into zinc.
- **Expected shape of failure does not follow a planar pattern, but rather like a half-spheroid.**
    - Wire failure occurs adjacent to region of peak confining pressure in zinc.
    - Agrees with Aux M4N wire fracture locations.
- **Quality of wire brooming can influence plastic strain levels in the zinc.**
    - Poor brooming allows bands of high shear strain.
    - Can potentially enable creep or plastic flow.



Wire failure pattern in FEM matches qualitative shape from forensics.



Zinc plastic strain is highly affected by level of wire brooming.

Structural Analysis of Voids and Defects

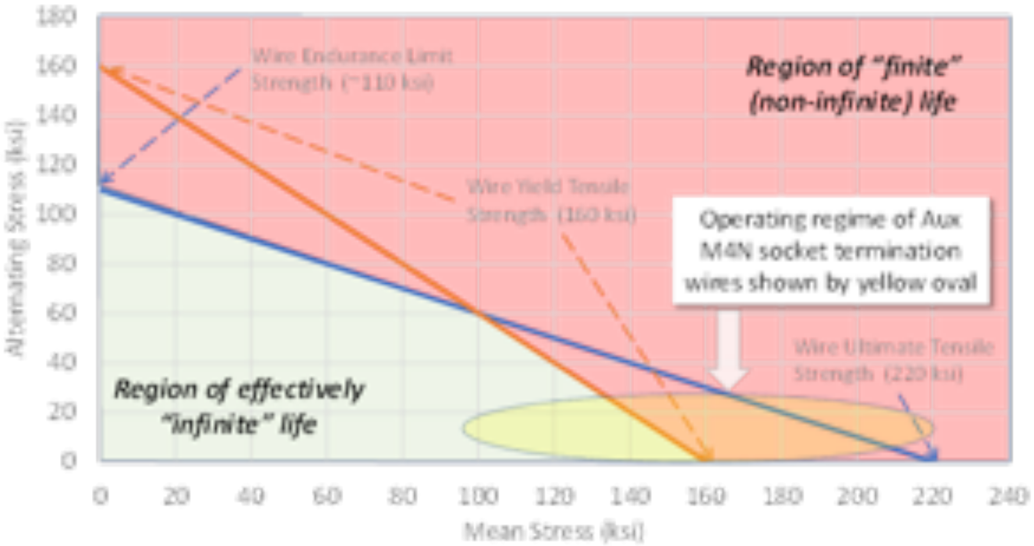
- **FEA considered the effects of corrosion on ends of eight wires which were cast protruding from zinc in contact with the socket.**
  - Analysis showed that corroded wire ends were not highly stressed due to corrosion being away from the narrow end of the socket; unlikely that as-identified corroded interfaces were detrimental to the load transfer mechanism.

- **A separate study evaluated the influence of Aux M4N casting voids and defects on critical wire stresses**
  - <u>Three void models: 1) toward the socket face side 2) midway down the socket length 3) toward the casting cap end.</u>
    - Voids were simulated by deletion of zinc material elements and showed negligible effects on outer wire stresses.
    - All void effects were highly localized within the socket volume and did not affect overall wire stress distribution outside the socket; highest stresses are near the socket face and are unaffected by voids away from socket face.
    - Analysis cannot rule out potential effects of voids on time-dependent behavior, local zinc damage, or damage to the wire/zinc interface that could have progressively increased plastic flow and affected wires elsewhere.
  - <u>A separate model had 20% of zinc volume removed to mimic the observed cavity tear just under the casting cap.</u>
    - Loss of near the casting cap resulted in no change to critical wire stress level and did not indicate a difference in socket capability.
    - Socket capability is influenced significantly by the zinc in the narrow side of the conical volume but is largely unaffected by the zinc near the casting cap
    - Unlikely that creep was accelerated due to observed cavity tear because zinc near casting cap is in low stress state.

FEA predicts that zinc voids identified in the Aux M4N forensic examination had a negligible effect on both zinc stress and maximum predicted wire stress located adjacent to the socket wire outlet

Structural Life Assessment

- **Aux M4N subjected to load fluctuations from daily winds, temperature cycles, hurricanes, and earthquakes.**
    - Sufficient load spectra data not available to quantify damage accumulation with high confidence.
- **Qualitative assessment showed that the design accumulates damage from cyclic loading and does not have a theoretical "infinite" life.**
    - Modified Goodman diagram demonstrates the relationship between mean stress offset, cyclic stress, and combined effect on life.
    - Relationship of cyclic loading and hold time (creep) further exacerbates findings about finite.
- **Mean stress sufficiently high that design will not accommodate significant cyclic or creep-related damage over "infinite" service life; cycles to failure were finite.**

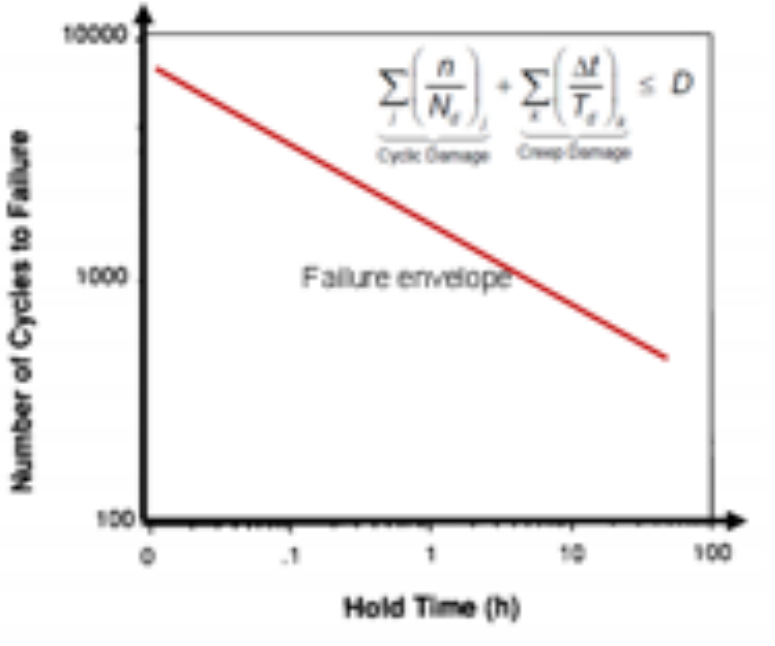


Structural Life Assessment

“Fatigue is the phenomenon leading to fracture under repeated or fluctuating stresses having a maximum value less than the ultimate tensile strength of the material. Fatigue failure generally occurs at loads that applied statically would produce little perceptible effect. Fatigue fractures are progressive, beginning as minute cracks that grow under the action of the fluctuating stress.”

–Metals Handbook Desk Edition, 2d ed., 1998, ASM International

- Forensic analysis found no clear evidence of fatigue cracking (e.g., beach marks, striations), but was not ruled out as small contributor; three wires had HAC w/ potential cyclic damage
- Design accumulates damage from cyclic loading and does not have a theoretical “infinite” service life; not accommodating of significant cyclic or creep-related damage, cycles to failure were finite.
- Finite element modeling found that damage due to cyclic loading could not be ruled out but was small compared with damage from sustained loads.



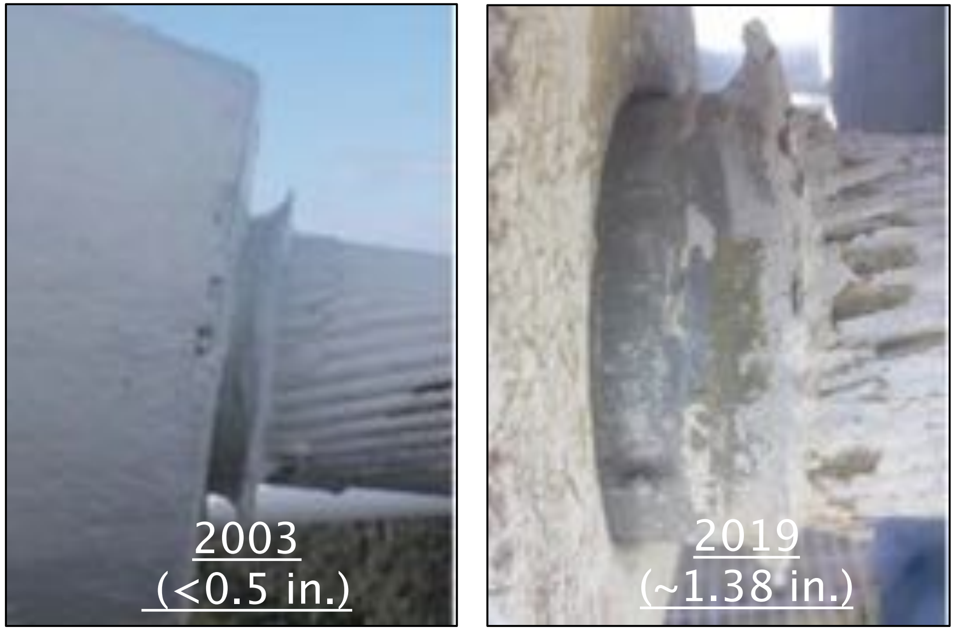
- No clear evidence of fatigue cracking (such as beach marks or striations)
- Design accumulates damage from cyclic loading and has finite life
- Contribution if any was small compared to sustained loading

Structural Life Assessment

Factors influencing socket failure:

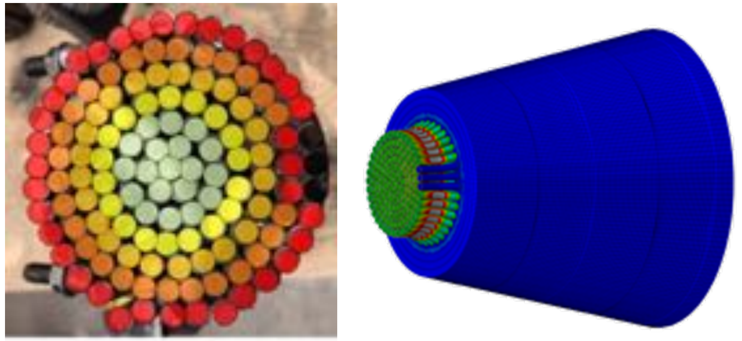
- Higher percentage of dead loads compared with transient loads.
- Predicted high stresses within zinc caused by sustained loading.
- As zinc creeped, outer wire stresses were predicted to increase.
- Negative structural margins further deteriorated over time due to zinc creep, eventually resulting in wire failure.

- Forensic evidence confirms contribution of slow zinc creep
- High % of deadload and low structural margin activated creep behavior in the zinc
- Inspection photos showing zinc extrusion confirm cumulative damage

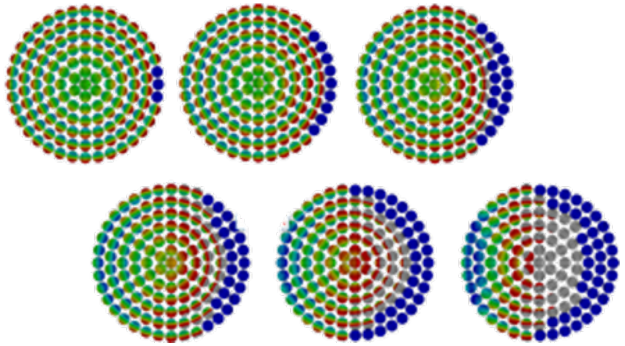


Inspection Photos showing Zinc Extrusion (representative Aux sockets)

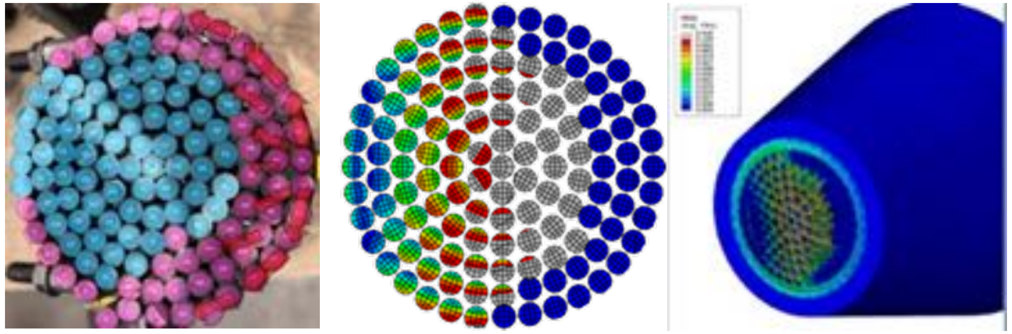
Failure Progression



Highest stress and lowest margin in RED
Three initial wire failures in black (left)
Modeling Simulation of initial wire failures (RIGHT)

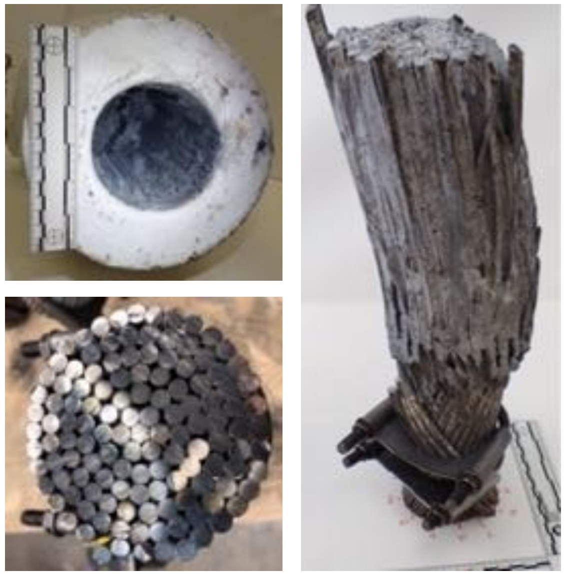


Analytical progression of wire breakage
advancing radially and inward from outside



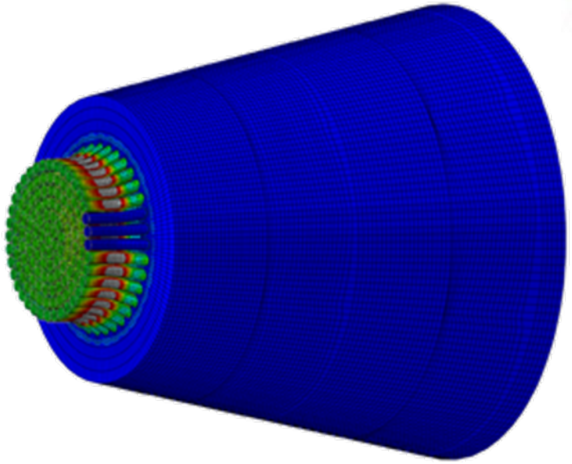
Comparison of forensics (left) with modeling
predictions just prior to failure (center/right)

- Analysis examined loads/stresses, and pattern of progressively failing wires adjacent to the socket termination. **(LEFT)**
- Varied number of failed wires to represent post-fracture configuration. **(CENTER)**
- Analytical progression of failure qualitatively matches forensics analysis including final zinc overload/cable core pullout. **(TOP/BOTTOM RIGHT)**



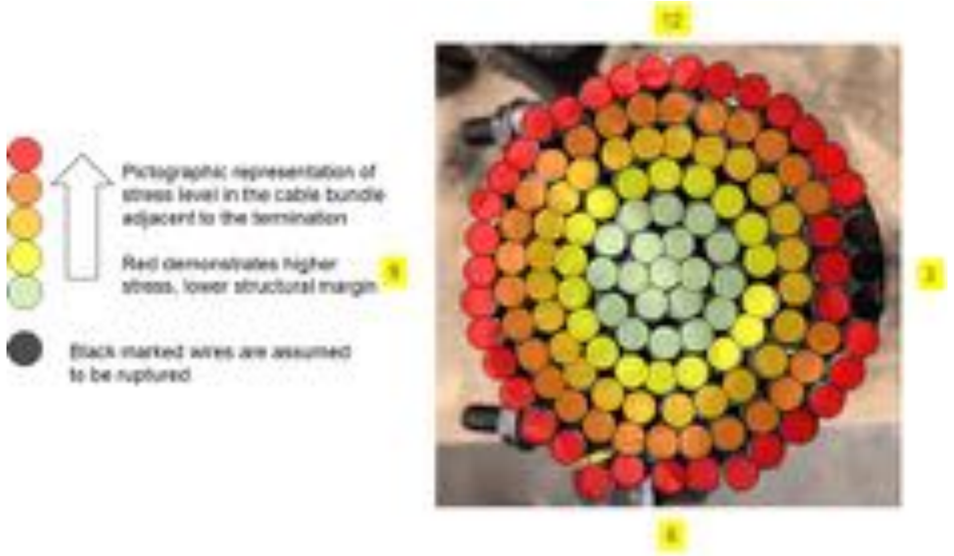
Failure Progression

- Analysis examined load redistribution and stress concentration effects of progressively failing wires adjacent to the socket termination.
  - Quantified stress increase of failure on adjacent wires.
  - Determined pattern of failure assuming select failed outer row wires.
  - Qualitatively compared to forensics evidence.
- Six finite element models varied the number of failed wires to represent post-fracture configuration.

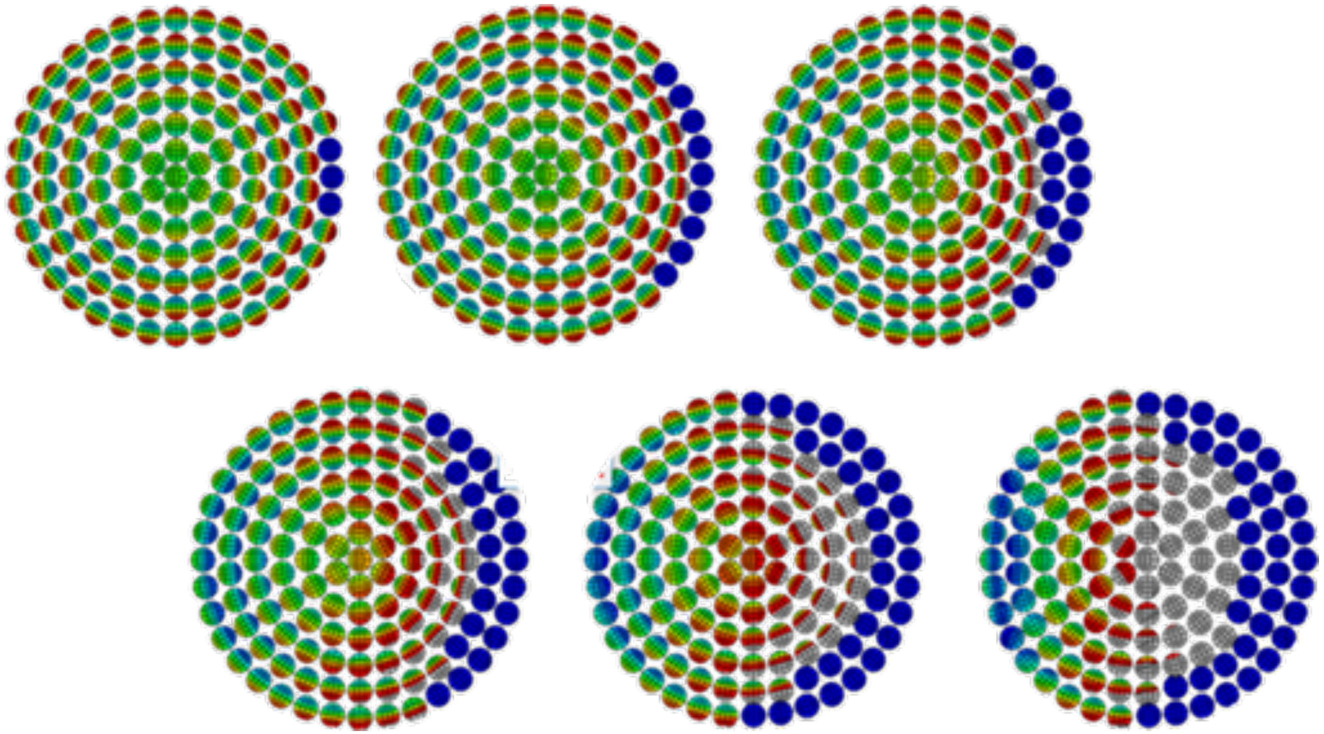


Fully circumferential 3D FEM showing three “failed” disconnected wires corresponding to same three wires indicated at 3 o’clock side in below image

- Qualitatively, the analytical progression of failure matches well with forensics analysis of wire mapping.
- Plastic strain of zinc shows a significant increase after wires fracture, indicating transfer of failure mode to zinc overload/cable core pullout.

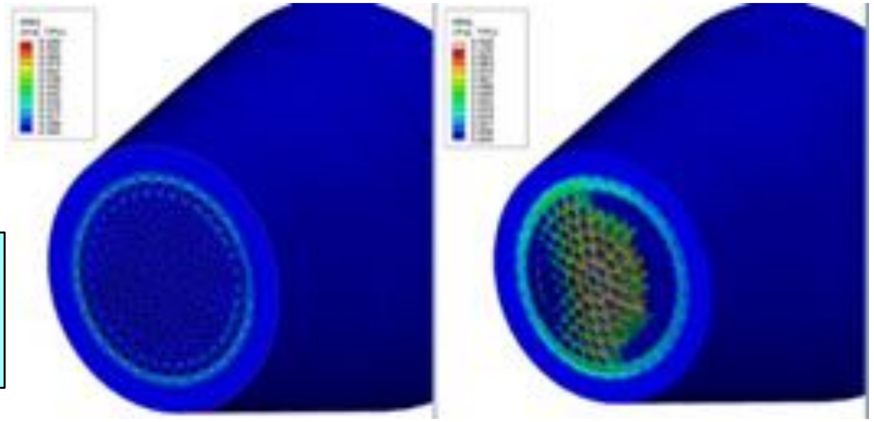


Failure Progression



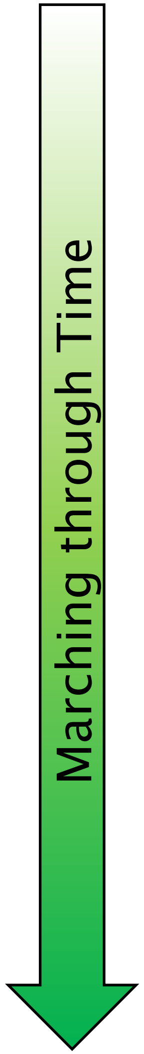
Two-dimensional cross-section of stresses at wire outlet show increasing stress as more wires fail, with tendency to fail radially and circumferentially; Stress increase for first three failed wires is ~5% to adjacent wires.

Forensic analysis ID’d which wires fractured (pink) vs. those that pulled out with cable core (blue)



Plastic strain in zinc is significantly increased after 38 wire failures; transition of failure mode to zinc overload

Failure Progression



Design

- (1) Design factor of safety of ~2.0, (2) Potentially unconservative loads model (3) high dead load % of total
- Design verification lacked specific testing of creep, cyclic load capability, end-of-life conditions, service life definition, and worst-case workmanship.

Build

- During manufacture, shrinkage occurred between casting cap and socket conical volume leaving a gap, w/ eight wires protruding through cast zinc; corrosion pathways by moisture intrusion into cast zinc
- During proof testing, select outer row wires yielded as zinc plastically deformed and seated within socket.
- Post-test inspection revealed acceptable levels of extrusion (<0.5 inch) from the socket base.

Operation

- Long-term dead load across the life of the observatory resulted in zinc flow due to creep and further increase of stresses in wires, thus decreasing their capability.
- Observatory operation may have further yielded select wires during survival loading events (e.g., hurricanes and earthquakes), resulting in stress hysteresis.

Inspection/Maintenance

- Periodic inspection found progressive zinc extrusion, increasing from <0.5 inch to 1.375 inches in 2019. Pass/fail criteria were not available, but industry experts and guidance indicate that 2019 measurements showed damage and a failing condition.

Failure Progression

Marching through Time

Initiation

- HAC and wire build defects on select outer wires are credible contributors to the initially failed wires.
- Select outer wires failed first, transferring load circumferentially and radially to adjacent wires, resulting in >5% stress increase.
- First wire failure modes were likely the slant shear failures due to the unbalanced confining pressure from zinc spelter at the outer row of wires near their outlet at the socket base.

Wire failure progression

- Further wire failures through the cross-section occurred, transitioning to cup-cone fractures for those wires containing sufficient confining pressure from zinc.
- After a critical number of the wires failed (56 in Aux M4N, analysis predicts fewer), there was insufficient confining pressure within the socket, and the zinc could no longer sustain the increasing shear stresses.

Socket Failure

- Failure mode transitioned to zinc “core” overload, where zinc was plastically strained to failure, and the observatory mass pulled the cable free from its socket w/ 70 remaining wire ends trapped in zinc spelter

Findings

The most probable cause of the Aux M4N cable failure was a socket joint design with insufficient design criteria that did not consider socket constituent stress margins or time-dependent damage.

- Structural design margin was initially low compared to industry recommendations, resulting in yielding wires.
- Deadload as a percentage of total load was significantly higher than typical industry applications.
- Zinc creep further degraded margins, primarily due to long-term sustained loading, and to a lesser extent from cyclic loading.

Design verification program did not explicitly consider the time-dependent effects of creep and cyclic loading on design capability, nor did it set service life intervals with passing inspection criteria.

- Did not account for a worst-case degradation, traceable to in-service inspection of features (e.g., zinc creep/extrusion).
- Hydrogen Assisted Cracking (HAC) and wire defects found in a few outer wires; may have contributed to initial wire failures.
- Inspections showed evidence of progressive zinc extrusion on several Arecibo sockets; evidence of cumulative damage.

Low structural design margin and atypical operating conditions revealed a vulnerability to zinc creep, environments, and long-term cumulative damage, which led to progressive Aux M4N socket failure and increased vulnerability to structural collapse.

- Failure mode was uncommon and insufficiently addressed within existing standards.
- Potential risk for similar designs/applications.
- Structure was not tolerant to cable failure due to the relatively low factor of safety.

Summary of Contributing Factors

- Relative approximate contribution to the Aux M4N socket failure based on root cause analysis

Category	Factor
Design Criteria	Insufficient Structural design code/standards
Design Criteria	High Sustained Load (dead load) as a percentage of Total Loads
Design Criteria	Low structural margins
Design Criteria	Inadequate consideration of time-dependent degradation mechanisms/creep
Inspection/Maintenance	Incorrect damage assessment of zinc extrusion – pass/fail criteria
Design Criteria	Incorrect load predictions
Fabrication/Build Defects	Socket wire defects and hydrogen assisted cracking caused initial fracture of some wires
Operation/Environments	Cyclic damage due to operation/wind/earthquakes/thermal
Fabrication/Build defects	Socket zinc defects, wire brooming
Operation/Environments	Corrosion
Fabrication/Build defects	Non-Conformance to drawing/specification
Inspection / Maintenance	Externally visible damage (corrosion/wire breakage)

Relative contribution

Recommendations and Go-Forward Plan

- NASA report provided to the University of Central Florida and National Science Foundation (*NASA/TM-20210017934).*

- NESC published a technical bulletin to inform NASA and Industry of concerns with zinc spelter sockets *(NESC Technical Bulletin No. 21-05).*

- NASA/WJE are in contact with the Civil Engineering community to examine existing codes to capture lessons learned.

https://www.nasa.gov/sites/default/files/atoms/files/tb_21-05_arecibo_failure_analysis_080221_final.pdf

National Aeronautics and Space Administration

NASA Engineering and Safety Center Technical Bulletin No. 21-05

Industry Recommendations from Arecibo Observatory Zinc Spelter Socket Joint Failure Analysis

A structural analysis and forensic investigation concluded that the Arecibo Observatory M4N socket joint failure in August 2020 was primarily due to cumulative damage caused by initially low structural design margins and a high percentage of sustained load, resulting in zinc creep deformation, progressive internal socket wire damage, and eventual loss of joint capacity. Open spelter sockets of this type are used throughout industry in stay cables. Recommendations are proposed to prevent failures of similar socket joints, including verification of positive stress margins in socket joint wires for all failure modes, periodic visual inspections with pass/fail criteria for zinc extrusion that are tied to structural qualification, and revisiting codes/industry standards to capture lessons learned.

NESC tech bulletin

Preliminary Questions and Answers

Loading Questions – Refer to WJE

- Why is 100 mph labeled “a survival loading with a wind speed” (pg. 26) when the peak cable load from such a wind is calculated to only be “622 kips” (pg. 88) in a cable calculated with an ultimate strength of “1314 kips.” (pg. 88)? This seeming contradiction is also illustrated in Figure C-4. Is there some other component expected to fail in such a wind? Why didn’t it fail in any wind speeds reported below?
- Why are there differing “peak recorded wind speeds” for Hurricane Maria all through the report? Are there multiple recordings? Are different people reading the “recordings” differently? “105 mph” (pg. 17), “110 mph” (pg. 100)
- Was the “finite element modeling” of this failure investigation compared to ANY of the original stress analyses done initially on the telescope or the analysis done for the redesign in the 90s?
- Was there any review of redesign work in the 90s? How good (or bad) were the earlier designs? You do say in the report, “WJE found that tension in the Aux M4N cable could have been up to 15% higher than reported on the original design drawing.” (pg 26). The ”could” in this sentence raises all sorts of questions. Were the calculations performed under the same set of assumptions? If not, why not? The original design values weren’t reported.

Design questions – WJE/NATHAN

- Were you able to confirm that Class A galvanizing was used on the wires (as specified):
  - FA did not find it on wires inside the socket (nominal). Refer to WJE for outside of socket.
- Any explanation why the choice of galvanization class A and why Class C (with better corrosion protection) was not used for this project?
  - Refer to WJE.

Preliminary Questions and Answers

- FA Questions - NATHAN
- **Were you able to assess the time sequence of wire failures in the outside wire layer through studying the oxidation rates (of zinc and iron) on the wire channel surfaces, corrosion on the fracture surfaces, and the lengths of the wire channels (within the outer layer of wires).**
  - Short answer is no. There was a fair amount of discussion between numerous contributors to this investigation regarding how much time-based evidence could be gleaned from corrosion evidence. One of the biggest concerns with using much of the corrosion evidence is the highly localized aspect to corrosion. Qualitative comparisons of the corrosion were made but kept separate between bulk zinc corrosion as one category and galvanic corrosion between steel and zinc as the other. Those were summarized in the corrosion slide in this presentation. In local regions, some evidence of time-based effects were noted, such as the corrosion evidence down the inner socket wall (e.g., NASA/TM-20210017934, Figure 7.2.5-1). Also, some observations were noted within the socket cavity (e.g., NASA/TM-20210017934, Figures 7.2.5-8 and 7.2.5-9), but these were also kept qualitative and we did not extend that to a quantitative analysis.
- **More information about the noted 5-degree misalignment between the socket interior and the cable and the influence of zinc creep on it, if any.**
  - The misalignment between the socket cavity interior and the cable alignment was attributed to the progression of failure, whereby wires predominantly failed on one side of the socket and from the outer rings to the inner rings, until the remaining intact wires could not sustain the load and slipped out. See NASA/TM-20210017934, Appendix A, Figures 219-221 to see how the cable/zinc slug appears to “lean” towards the side with only outer wire failures.
  - Evidence of creep from recrystallization in the zinc was only analyzed in the front of the socket, from the cavity out to the socket wall, where the confining pressure was among the highest based on structural analysis. Structural analysis indicated that the stresses are not uniform within the zinc casting and, the further back in the socket you go, the lower the stress and the less influential the zinc is on the overall strength of the joint. So, near the back of the zinc casting and wire strand ends, I would expect the creep evidence to be more confined close to the wire, if evident at all.
- **Clarification on the reported tolerance issues between measured and specified dimensions. Basis for the acceptability of the reported large tolerances? Were the "specified" values taken from the drawings or the company product catalog?**
  - From discussion with industry experts, each foundry defined the socket casting dimensions to meet the drawing tolerances. Specified values were taken from the Structural Strand and Wire Rope Catalog published by Wirerope Works in 2007. There were no specified required dimensions on the drawings available, nor were catalog values from the time of design and installation available.
- **Relate the extrusion amounts at the exit of the socket with the deformed surface at the back of the socket. The report refers to casting defects (poor bond between zinc and wire) at least in some locations. How influential were these casting defects?**
  - The brittle fracture region in the back of the socket peeled away from its mating fracture surface, so it has a varying displacement value between those mating surfaces. But the larger displacements are in line with the displacement seen between the photos of the extrusion. Wire channel cavities, between a wire end’s final resting spot within the zinc casting and its original location, show anywhere from no displacement to multiple inches of displacement. How interconnected some of these displacements were is not entirely clear. So, attributing a time for the brittle fracture region to begin growing did not seem conclusive, but there is a strong likelihood that it was part of the cumulative damage that contributed to the, less than, 0.9 inches of extrusion between the 2003 and 2019 photos.
  - The poor bond between the zinc and the wire does include many different areas within the zinc casting, the majority identified toward the back of the cavity, but it also includes the fact that some of the wires that were mechanically removed (e.g., AE, N, and the 8 wires that were protruding through the zinc casting to the socket wall) showed zinc oxide along their surfaces down to their fractured ends. The fact that these wires show evidence of zinc oxide corrosion down to the fracture surface, but did not pull free with the zinc slug, suggests that the amount of oxidation along the wire lengths was not significant enough to affect the ability of these wires to realize their full tensile strength. While the zinc oxide corrosion evidence among the remaining fractured wire ends was destroyed during the hydrochloric acid etch to reveal all the wire fracture surfaces within the socket, the wire surfaces still embedded in the remaining zinc, in both the socket and the slug, can still be mechanically removed to better characterize the corrosion around all the wire surfaces.

NESC Board Findings and Recommendations

Findings

F-1. The Aux M4N socket build process and original construction was typical of zinc spelter open-socket terminations.

F-2. Zinc extrusion of Aux M4N socket as documented in 2019 indicated an unquantified degree of damage and a nonconformance.

F-3. Creep behavior of the zinc spelter socket termination constituents (zinc or broomed wires) is not a failure mode typically evaluated for these sockets.

F-4. Socket housing dimensions were within wire rope catalog specifications.

F-5. The Aux M4N cable met drawing requirements for a 3.25-inch diameter cable (see Appendix D).

F-6. The Aux M4N cable end section and socket cavity are skewed compared with the socket's longitudinal centerline axis.

F-7. Gas bubbles located above wire ends were trapped during the solidification process.

F-8. Smaller-sized porosity inherent to the casting process was found intermittently throughout the bulk zinc.

Findings (cont.)

F-9. Fifty-six of 126 wires fractured in the socket.

F-10. Seventy of the 126 wires did not fracture; the zinc failed before the remaining wires failed.

F-11. Wire surface defects were found on five fractured wires. Defects on two wires likely influenced the fracture, one of which was an initiation site for probable HAC.

F-12. Forty-four of the 56 wire fracture morphologies were cup-cone fractures, nine were shear fractures primarily from the outer ring, and the remaining three were mixed-mode fractures, which included a progressive failure mechanism believed to be HAC (one cup-cone/HAC and two shear/HAC).

F-13. Outer ring wires typically had less necking than inner ring wires and are expected to have failed first.

F-14. Excluding the HAC fractures, none of the wires examined by microscopy and SEM exhibited fatigue fracture.

F-15. Wire imprint region of the zinc in the back of the socket cavity is heavily corroded and poorly bonded to the wire ends.

F-16. The intergranular cleavage region of the zinc in the back of the socket cavity is corroded, with surfaces that follow the grain boundaries and the ends of the grains lifted up (i.e., a peeling failure).

Findings (cont.)

F-17. Zinc casting was composed of elongated grains, with significant variation in both grain size and length.

F-18. Metallography shows no evidence of fatigue cracking within the zinc, but minor additional contributions of cyclic loading damage may not be discernable from the overall contributions of sustained loading damage, as both would manifest themselves in deformation mechanisms (e.g., twinning and slip bands) present within the zinc.

F-19. The zinc nearest the base, adjacent to the cable/zinc boundary, was determined to be in the late secondary or tertiary stage of creep.

- Zinc creep becomes a design consideration when its homologous temperature exceeds 40%, which is the case for zinc at room temperature.
- Grains near the cable/zinc boundary are fully recrystallized and have grain boundaries that are generally oriented 45° to the stress direction.
- Cracks appear predominantly intergranular, which is typically associated with creep rupture at high temperatures and low speeds of deformation.

F-20. Significant corrosion was found in the upper two-thirds region between the socket housing and the zinc casting outer diameter, while negligible corrosion was found in the lower third.

Findings (cont.)

F-21. Moisture intrusion, which led to zinc/wire corrosion, followed a path that included a gap between the inner socket wall and the zinc casting, wire protrusions from the zinc, cracks in the bulk zinc, and the wire surfaces of individual wires.

F-22. Evidence shows corrosion generally had a minimal effect on wire-zinc bond strength.

F-23. Wire mechanical properties meet ASTM specification.

F-24. Zinc mechanical properties in the Aux M4N spelter have significant variability as a function of grain size and directionality.

F-25. Observatory dead load resulted in sustained cable tensions within 20% of the maximum expected cable tension.

F-26. Finite element modeling predictions quantitatively agree with rated/measured wire breaking strength.

F-27. Finite element modeling predictions were qualitatively in agreement with the NASA forensic analysis:

- Maximum wire stresses predicted followed the stepped pattern observed in the forensic analysis.
- Outer wires were predicted to fail in a shear failure.
- Inner wires were predicted to fail in a cup-cone failure mode due to the compression effects of the zinc on the wires.

Findings (cont.)

F-28. For a large range of realistic zinc material properties, all models predict that outer wire stresses are near ultimate strength of individual wires, even at operational observatory loads, demonstrating low or even negative margins of safety for the M4N socket.

F-29. The socket design had low wire structural margins and a large percentage of sustained loading, which made the design susceptible to a creep-dominated failure, likely accelerated by fluctuating cable loads.

F-30. Decreasing brooming quality results in increasing stresses in the outer-row wire and reduces margin for designs operating near their strength capacity.

F-31. Analysis predicts that stresses in the zinc and wires are not affected by the zinc voids identified in the forensic examination of the Aux M4N socket.

F-32. Socket joints in the Arecibo Observatory application were subjected to a relatively higher percentage of sustained cable load versus total load compared with a survey of bridge designs, increasing susceptibility to creep.

F-33. The Arecibo Observatory had an effective design factor of safety of ≤1.83, which is significantly less than the minimum suggested by literature (i.e., >2.1) to ensure structural redundancy in the event of cable failure.

Findings (cont.)

F-34. The Aux M4N design had insufficient design criteria and a low structural margin, which were insufficient to accommodate time-dependent damage mechanisms.

F-35. The Aux M4N socket joint design did not explicitly consider time-dependent mechanisms for the Arecibo application to establish an end-of-life capability.

F-36. Low socket design margin and atypical operating conditions revealed an unexpected vulnerability to zinc creep and to long-term cumulative damage, which led to progressive zinc/wire failure of the socket.

F-37. The effective design factor of safety was significantly less than the minimum suggested by literature and was insufficient to ensure structural redundancy in the event of a cable failure.

Recommendations

R-1. The NSF should section and examine additional Arecibo sockets, including auxiliary sockets and backstays, to understand whether the Aux M4N had unique features versus other sockets and to understand why backstays had zinc extrusion but did not fail. This will increase the understanding of progressive failure mechanisms in sockets similar to Aux M4N and inform guidance on best practices for spelter socket design and usage.

The team recommends research on the mechanics of spelter sockets, the development of inspectable pass/fail criteria for time-dependent failure modes, and risk assessment for sockets in service.