Methodology for Predicting the Service Life of High-temperature Low-sag Conductors (Phase I)

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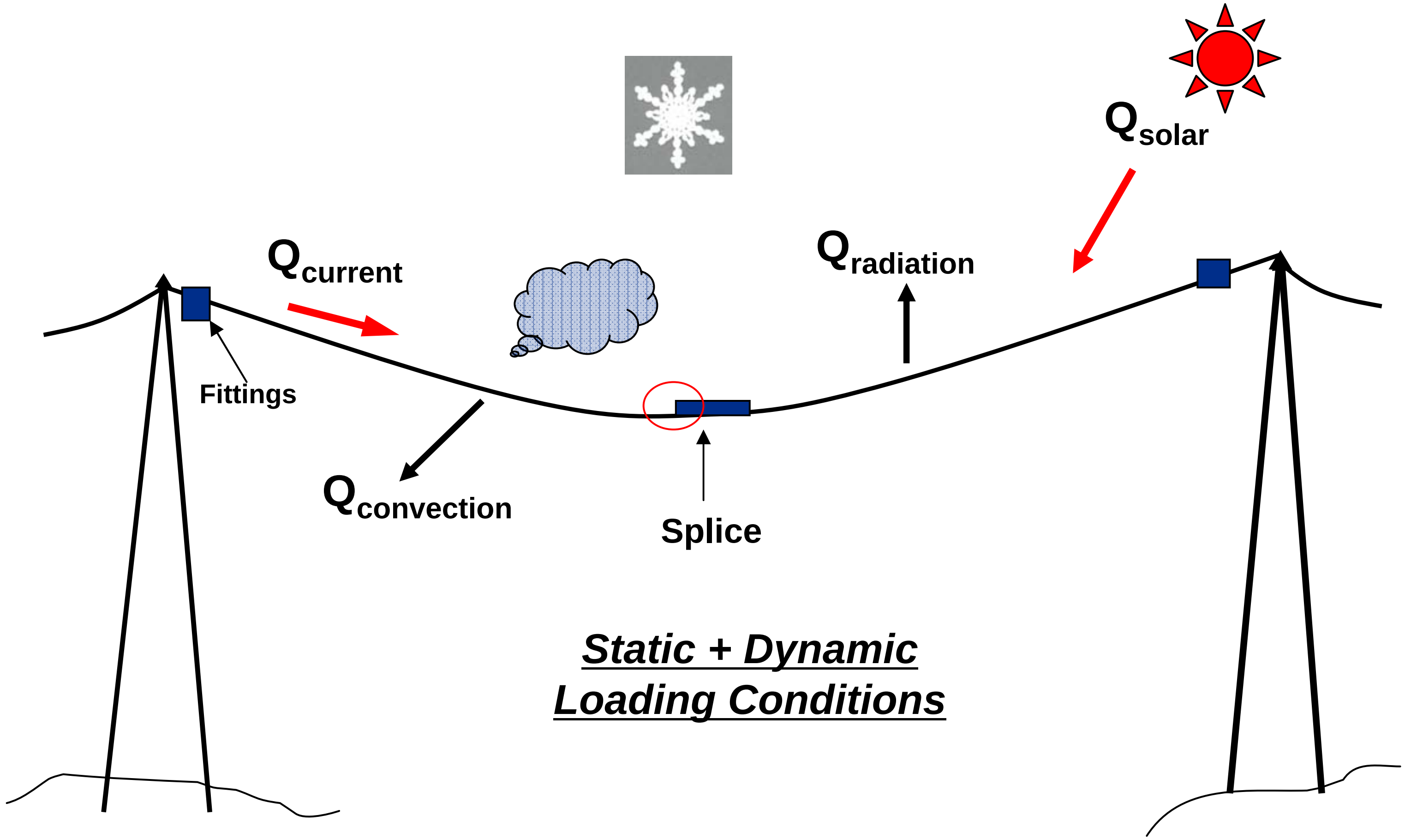
Presentation Outline

- Background
- Goals of the project
- Approach
- Work in Progress
- Future Work

ACSR Conductor

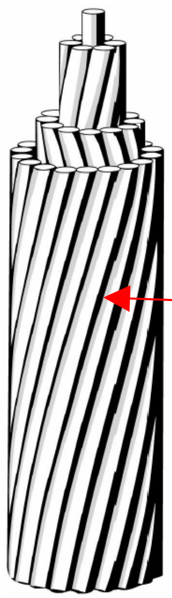
- The overwhelming majority of overhead transmission lines use steel-reinforced aluminum (ACSR) conductors.
- ACSR may be operated at temperatures up to 100ºC and, for a limited time during emergencies, at temperatures as high as 125°C.
- These temperature limits constrain the thermal rating of a typical 230-kV line to about 400 MVA.

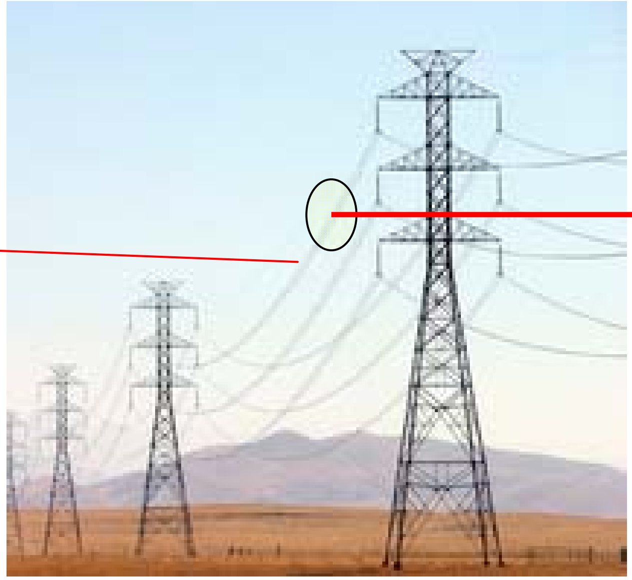
The Impact of Service Environment on Conductor System Aging



<u>Static + Dynamic Loading Conditions</u>

The Most Likely Weakest Link in A Conductor System – Splice Connector

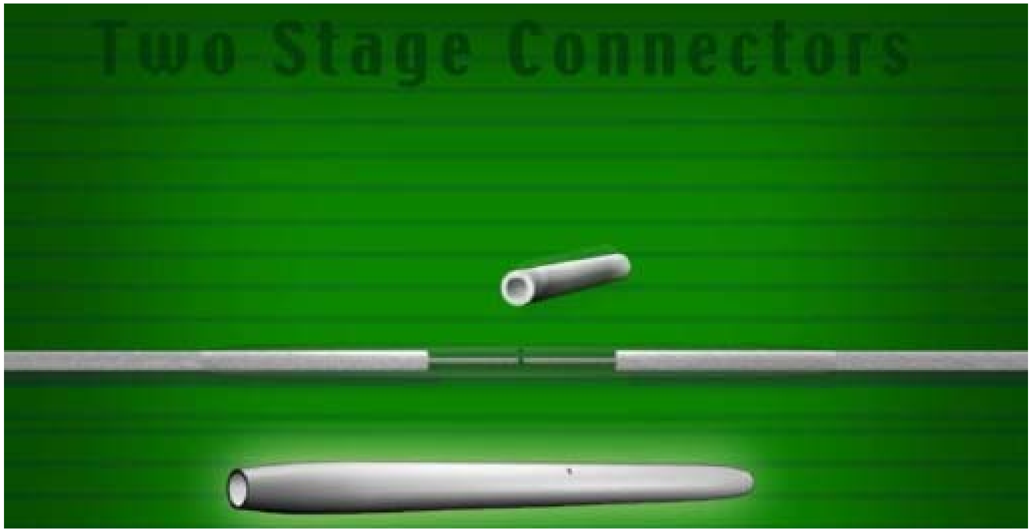




Compression splice connector fittings: (top) the two-stage fitting (TSC), (bottom) the single stage fitting (SSC).

Especially at higher operating temperature!

Single Stage and Two Stage Connectors



Accelerated Conductor System Aging

- Increase of power demand and lack of new infrastructure results in higher operation temperature of existing transmission line
- Accelerated connector aging due to higher operating temperatures:
  - Significant increase in resistivity, i.e., less efficient transmission of electricity,
  - Significant reduction in the connector clamping strength, ultimately resulting in separation of power line.

Main Focus

To assess the long term impact of thermal cycling fatigue and creep on conductor life.

- ✓ **ACSR conductor/splice interface**
- ✓ **Single stage splice connector fitting**
- ✓ **Life time prediction of conductors/splice**

Our Vision

Long-Term Goals

To develop an automated visual expert system that is equipped with detailed geographic information, power-time history, and the material aging models,

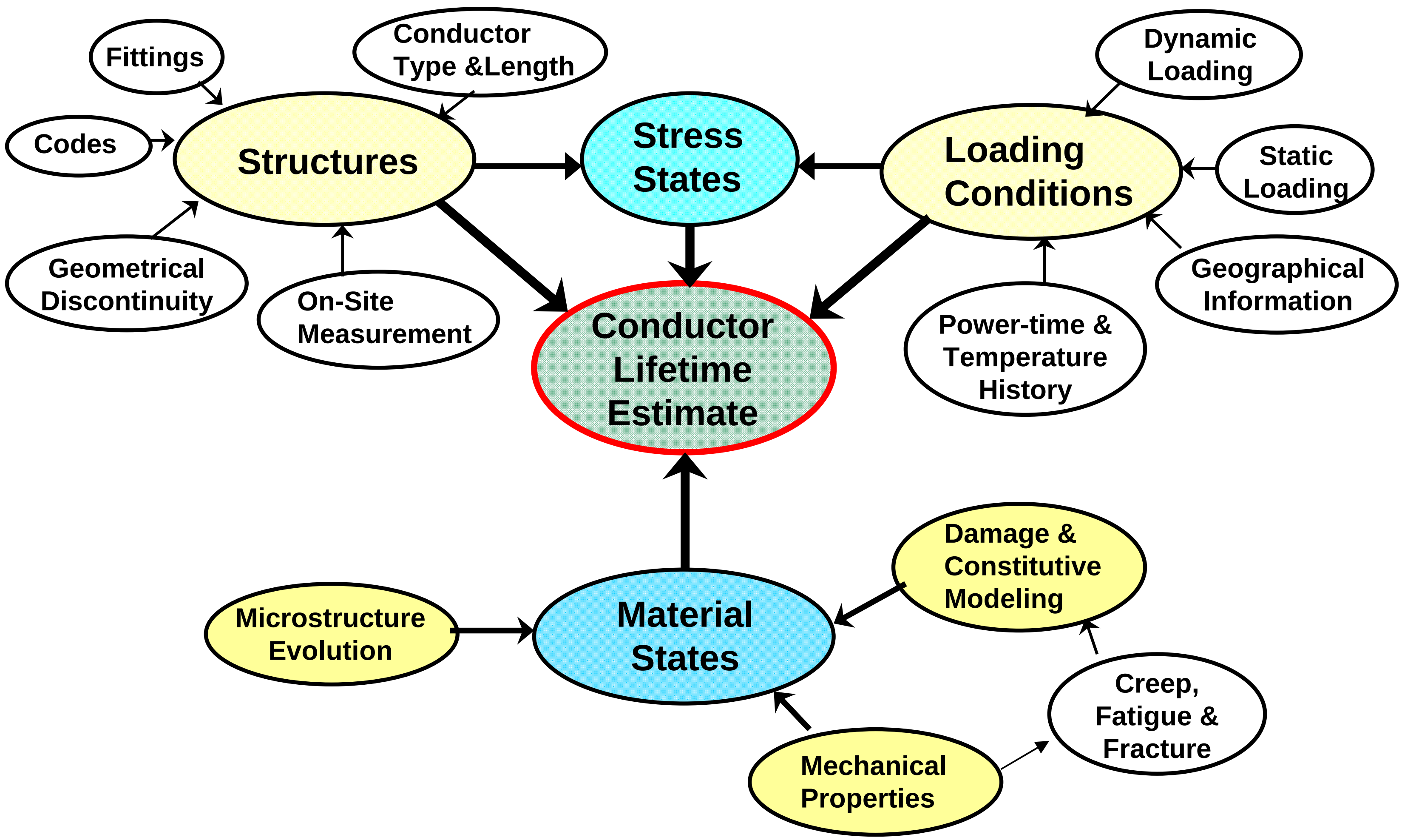
that is capable of

- **providing an accurate estimate of power line performance and lifetime estimate; and**
- **providing a basis for developing industry guidelines, and consensus standards.**

Benefits

- Optimize existing power grids
- Prevent conductor system damage
- Accelerate decision making processes
- Reduce maintenance cost & outages

Parameters Involved in Conductor System Lifetime Estimates



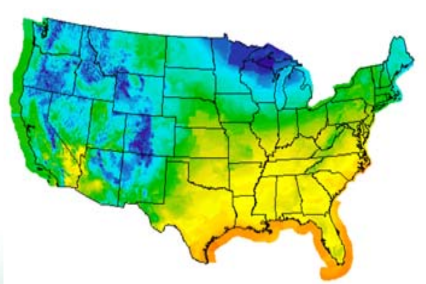
Goals

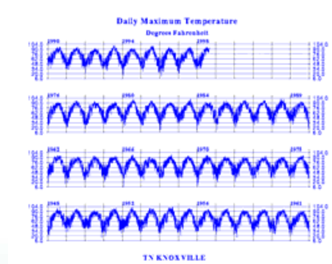
Building System Performance Operator

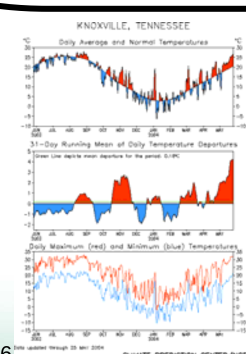
One objective of this project is to identify/derive constitutive equations to describe the behavior of transmission line materials

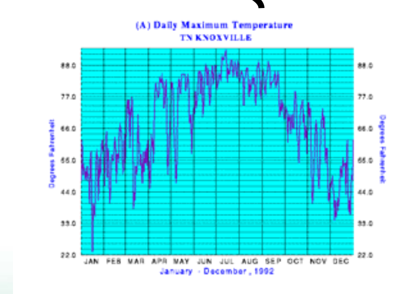
Black box

input → Aging Model for Aluminum Steel → output





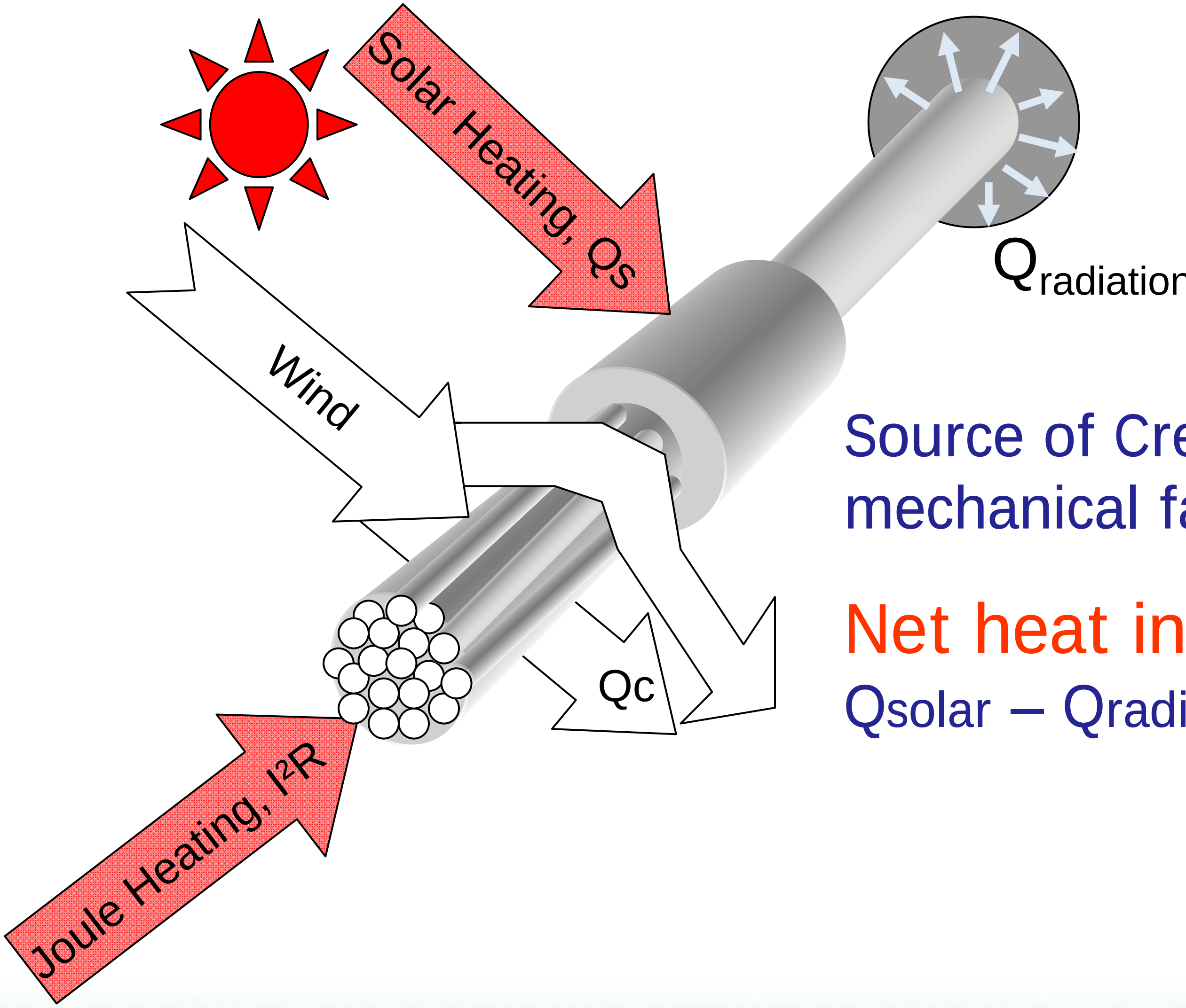




Layout of Technical Plans for Conductor Aging Research

1. Thermo-mechanical evaluation and physical characterization
2. FEM modeling, inelastic deformation models
3. Confirmatory splice connector structural evaluation
4. Investigation of microstructural evolution
5. Incorporation of models into computational tools

Thermal-Mechanical Evaluation & Physical Characterization



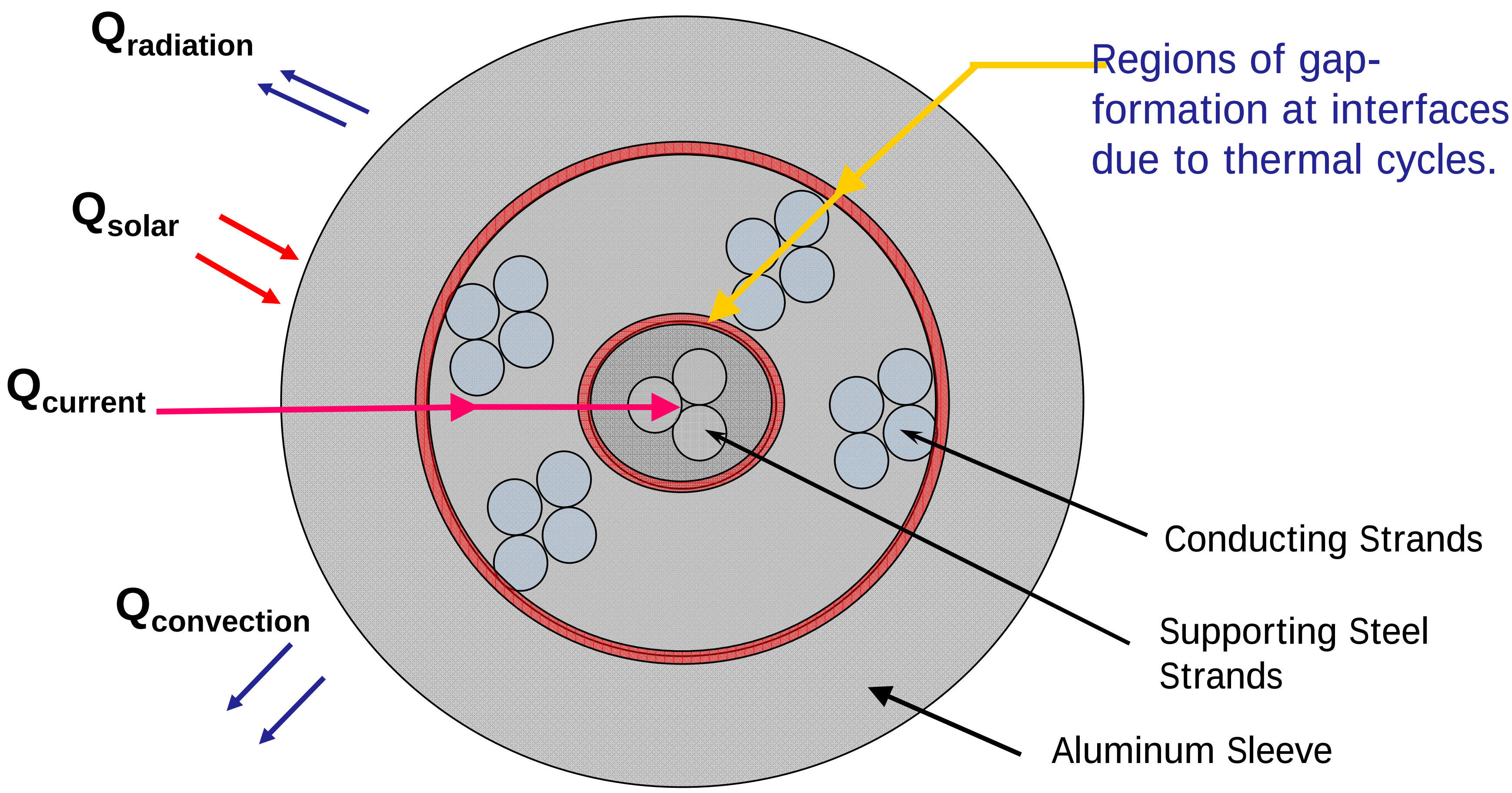
Source of Creep and thermal-mechanical fatigue damage

Net heat input = Qcurrent + Qsolar – Qradiation – Qconvection

Thermal Cycles induce Gap Formation and Clamping Stress Relaxation

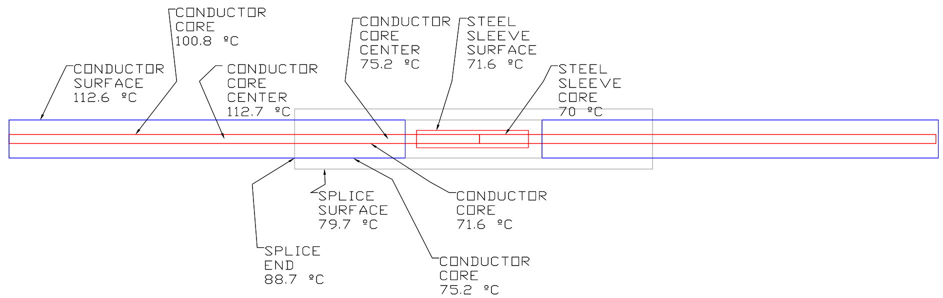
- Thermal-mechanical properties mismatch at interfaces, and
- Cumulative damage taking place (creep and fatigue) at the fitting region results in gap density increase and the less compressive binding stress at these interfaces.
- The consequence is two-fold
  - Reduce electric and thermal conductivity
  - Reduce connector binding stress and ultimately results in conductor separation & failure.

The Impact of Trapped Heat Source



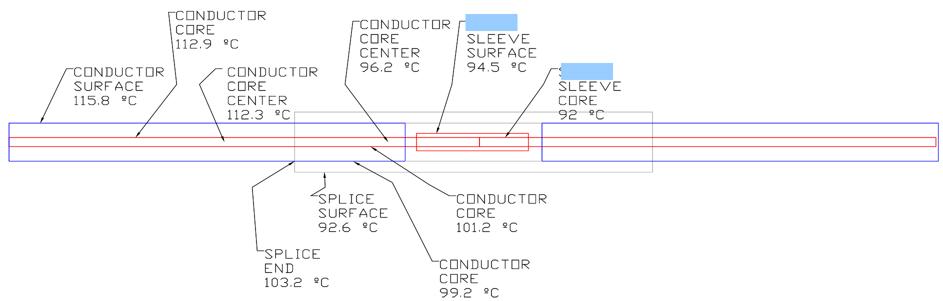
Temperature Profiles of ACSR SSC and TSC Connector Fittings

TWO-STAGE



Conductor surface temperature: 115°C

ONE-STAGE



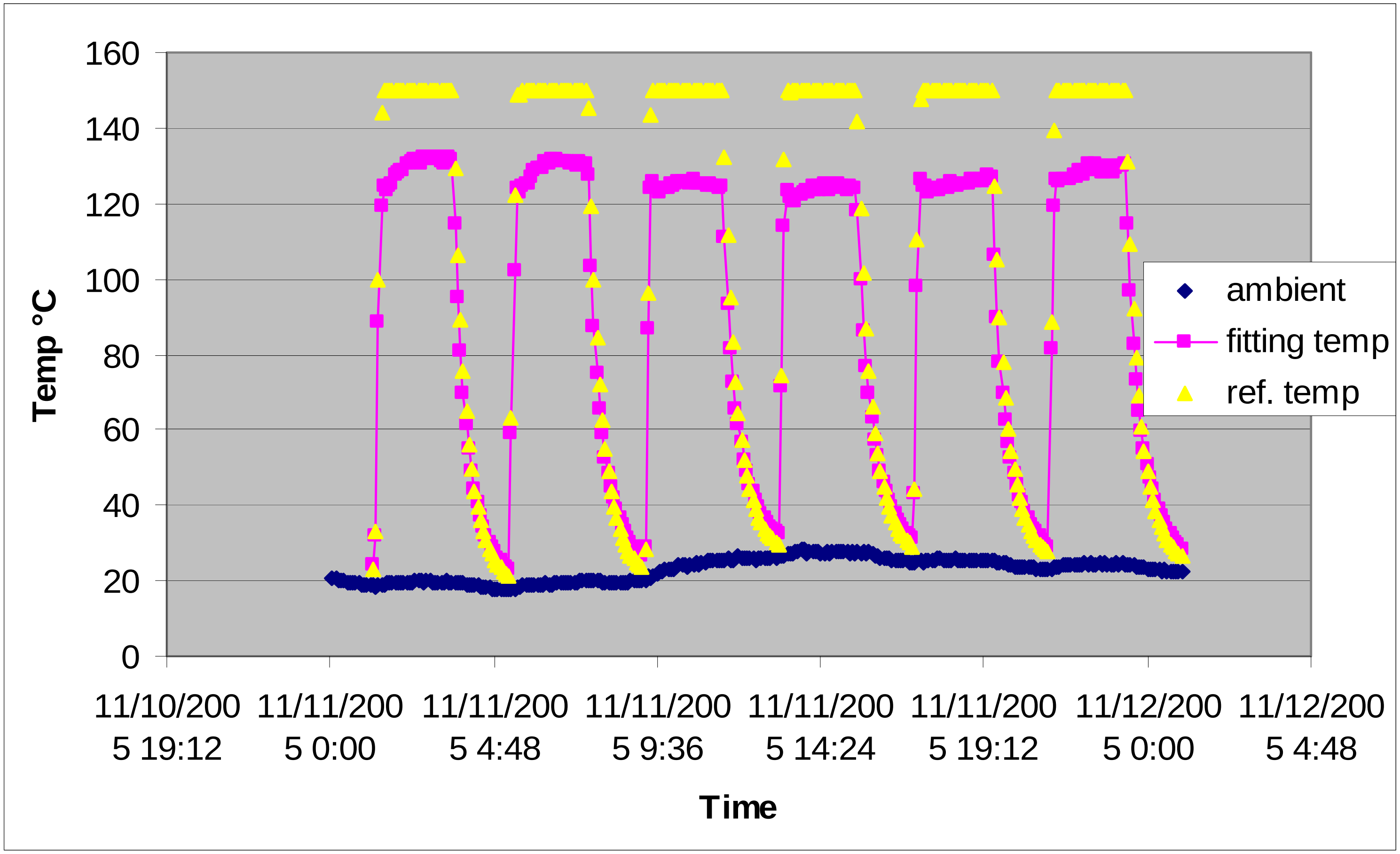
For a new system, the connector temperature is lower than the conductor surface temperature.

For a conductor surface temperature of 115°C: after nominal cycles

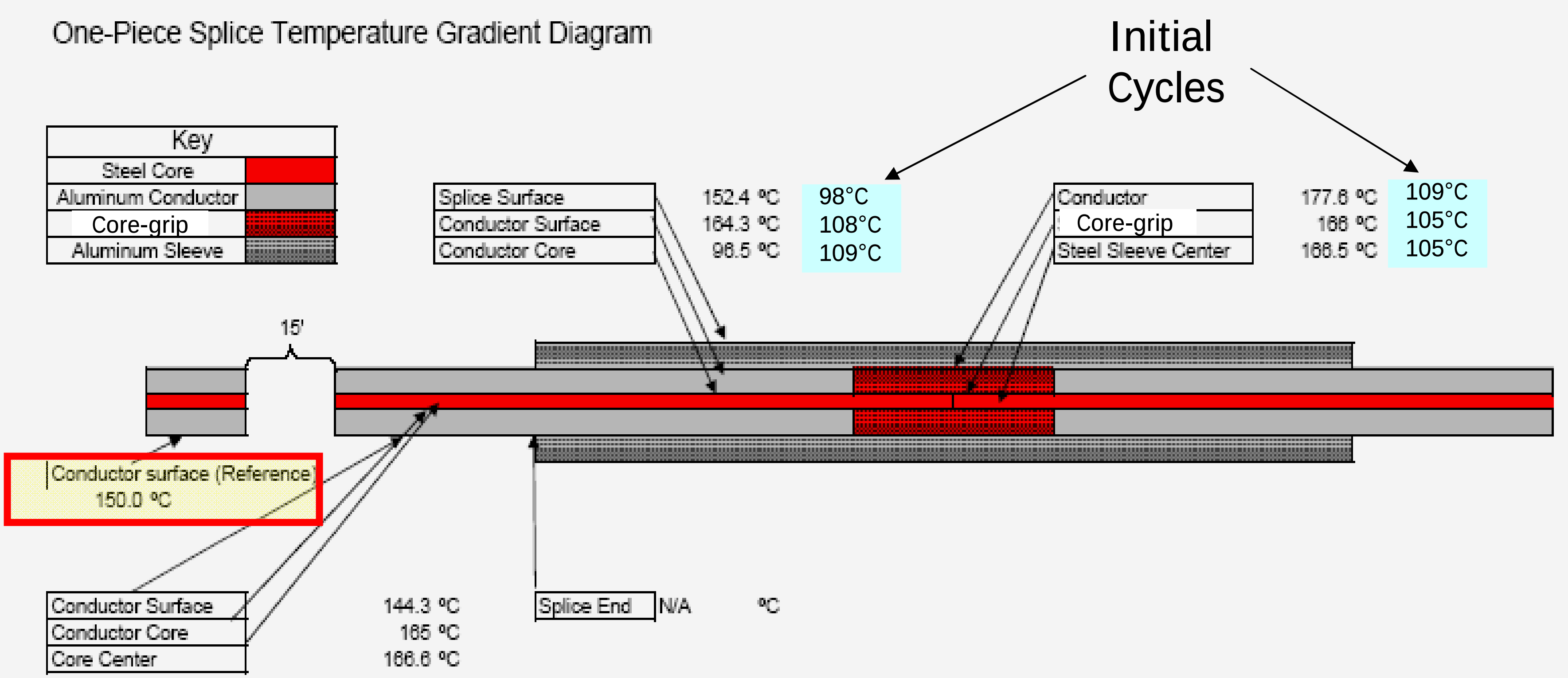
SSC interface temperature: 99°C; TSC interface temperature: 75°C

In collaboration w/ EPRI Solutions

Thermal Cycles Frequency
12 hours / 6 cycles



Temperature Profiles of ACSR SSC Connector Fittings



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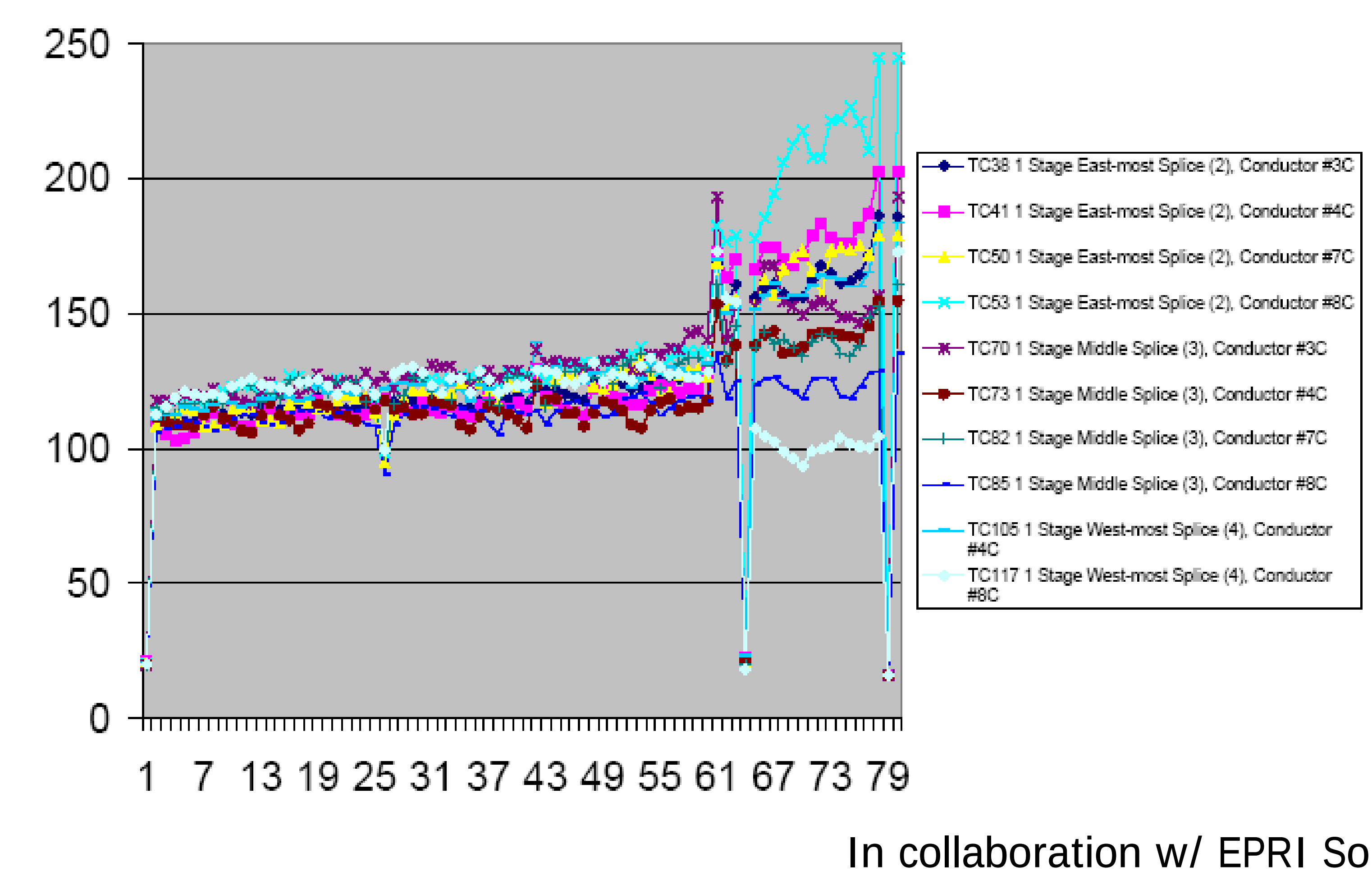
Thermal-mechanical

Temperature increased dramatically in ACSR SSC after 65 Thermal Cycles



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Analytical FEM Consideration

- 2D versus 3D simulation of SSC fitting
  - 2D for core-grip section
  - 2D & 3D for conductor section
- Quasi-static ramp loading vs. dynamics loading simulation
- “Contact Pair” concept of “General Contact”

Residual Stress Evaluation Effort

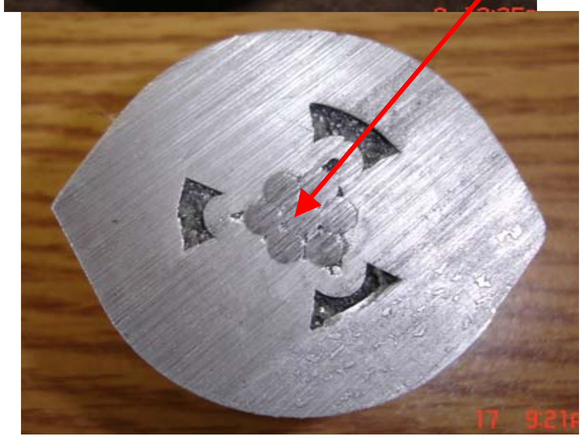
- Analytical evaluation of SSC fitting forming mechanism
  - ✓ Issue on real model (Drake) or simplified model
  - ✓ Issue on "contact" problem
  - ✓ Issue on dynamics simulation
- Non-destructive residual stress evaluation benchmark
  - ✓ Issue on penetration
  - ✓ Issue on joint compound
  - ✓ Issue on noise and sensitivity

Primary Index for SSC Integrity

- The compressive residual stress in SSC provides constraint to confine and secure the conductor.
- This compressive residual stress is expected to be decreased due to thermal cycles.
- The degradation of the compressive residual stress in SSC provides a good primary index for an effective lifetime estimate.

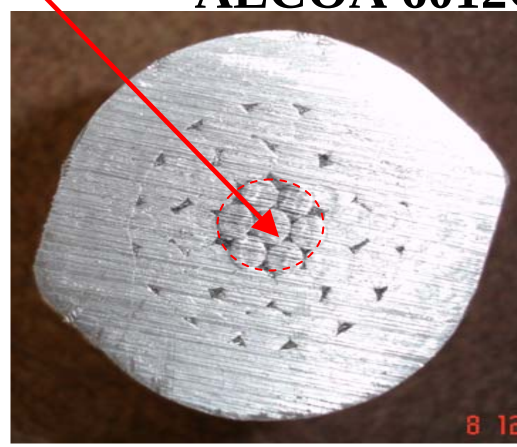
Single Stage Splice Connector

Core-Grip Section



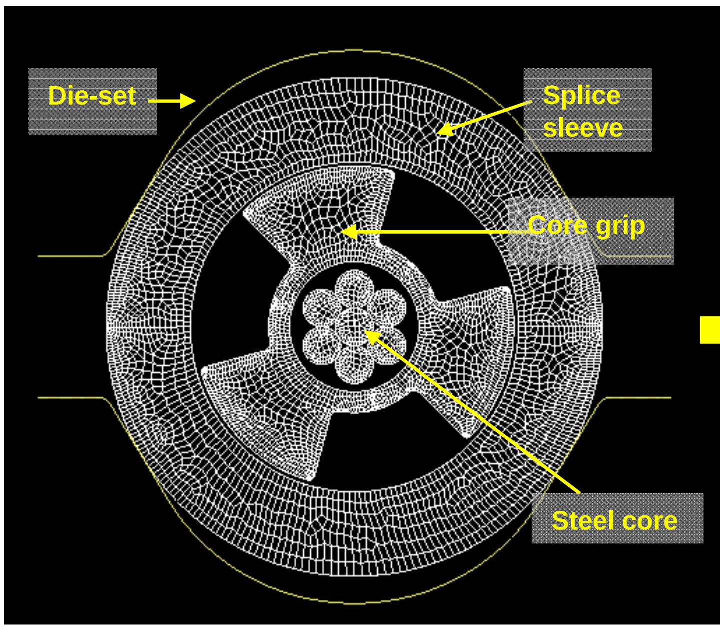
Steel Core

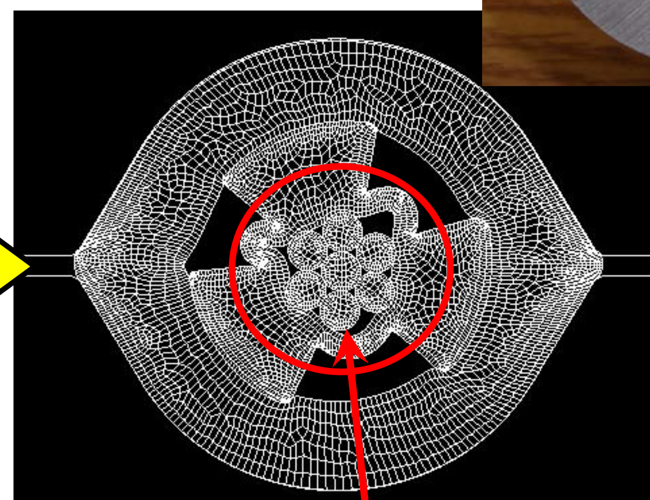
ALCOA 6012CD die



Conductor Section

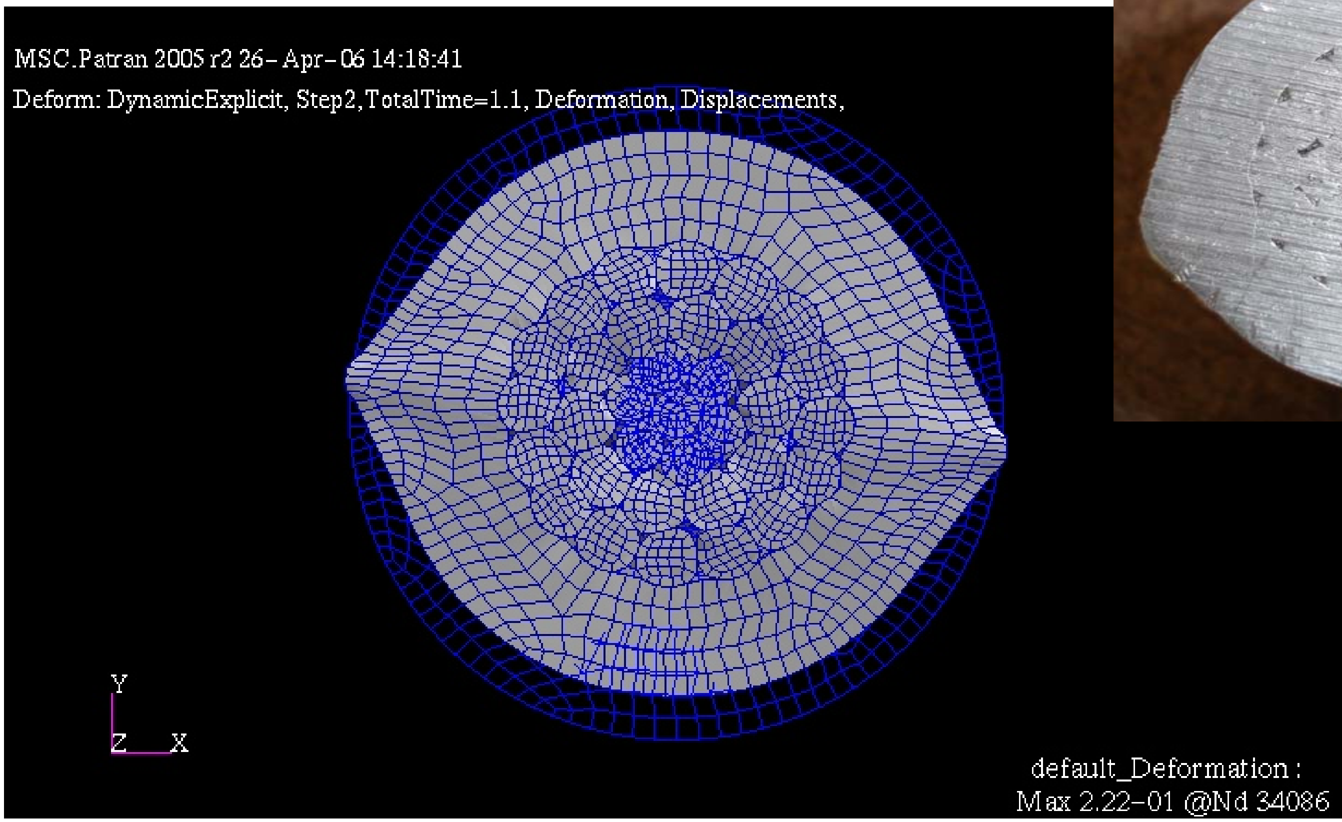
Finite Element Model of an ACSR SSC Drake Conductor



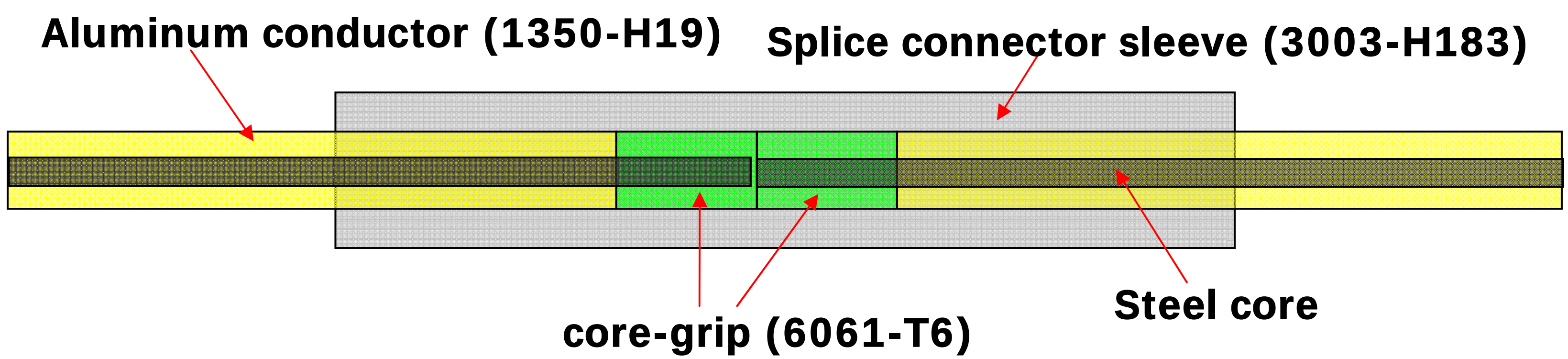


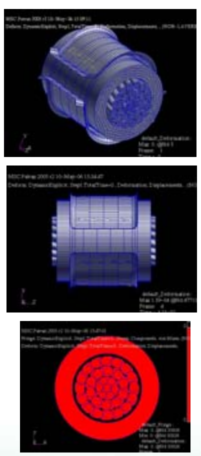
Contact areas at material interface are limited

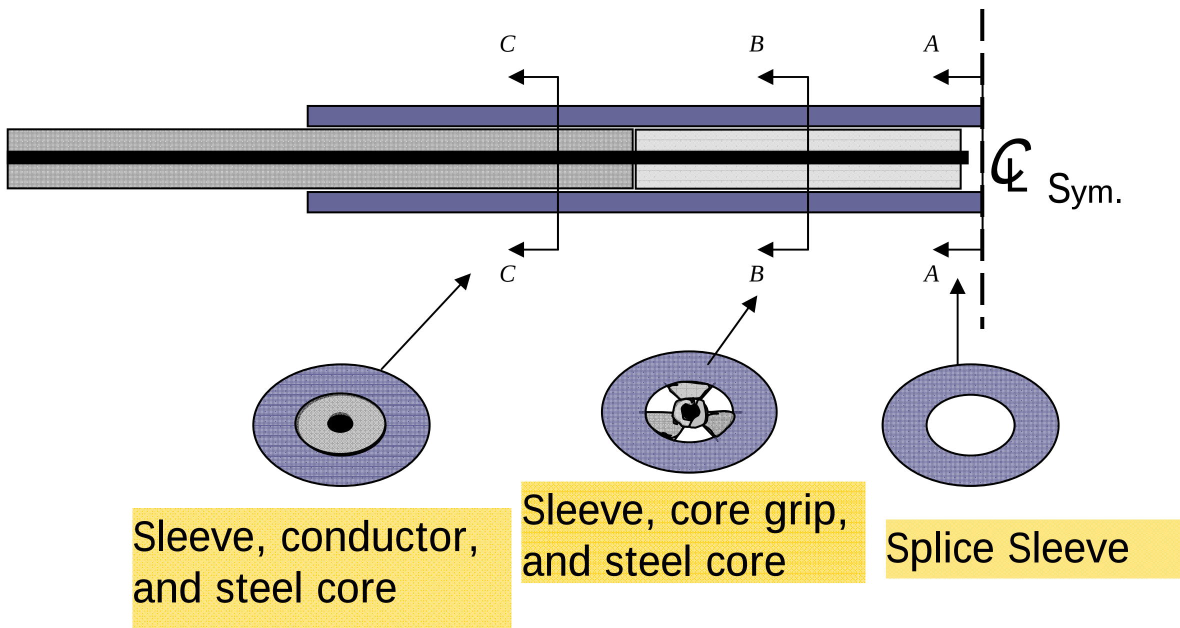
FEM Simulation at Conductor Region

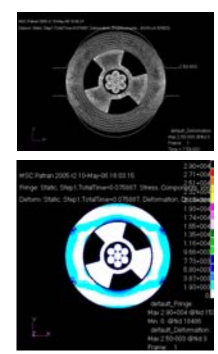


Load Transfer within SSC Fitting



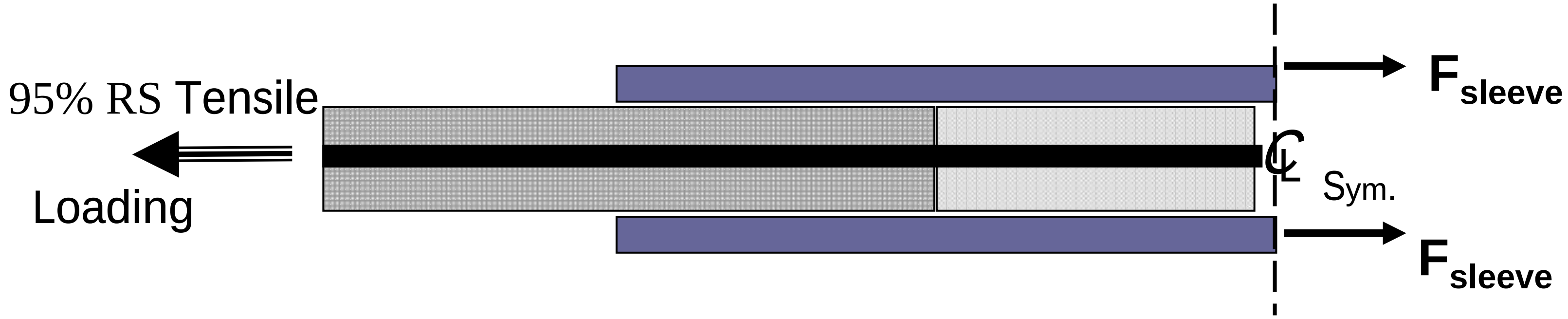




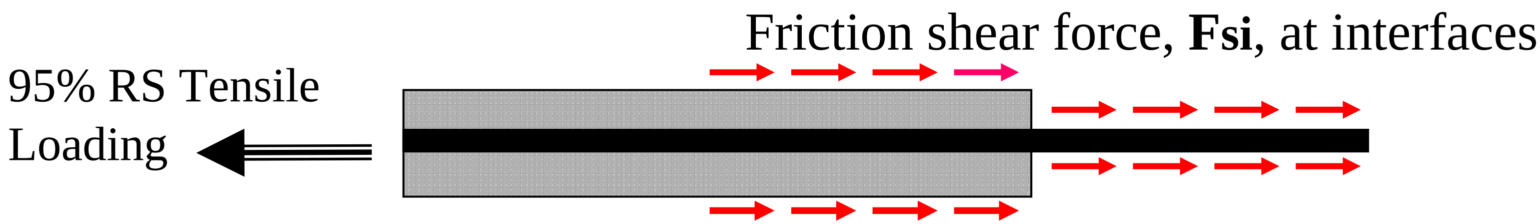


FEM Analysis

Load Transfer within SSC Fitting



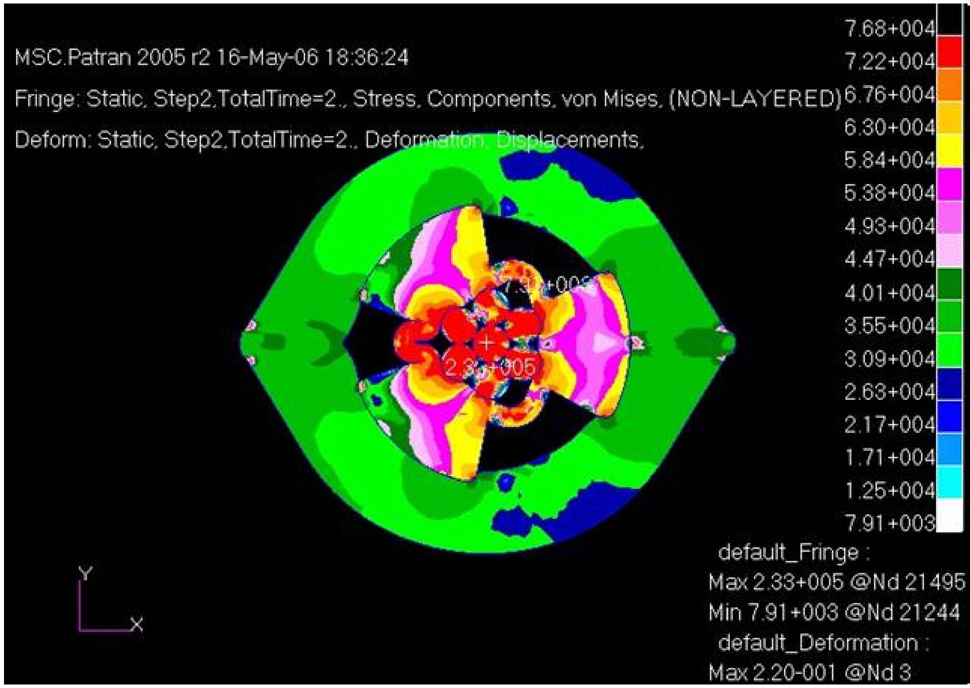
Sleeve carries the full rated breaking strength at the middle section of the sleeve



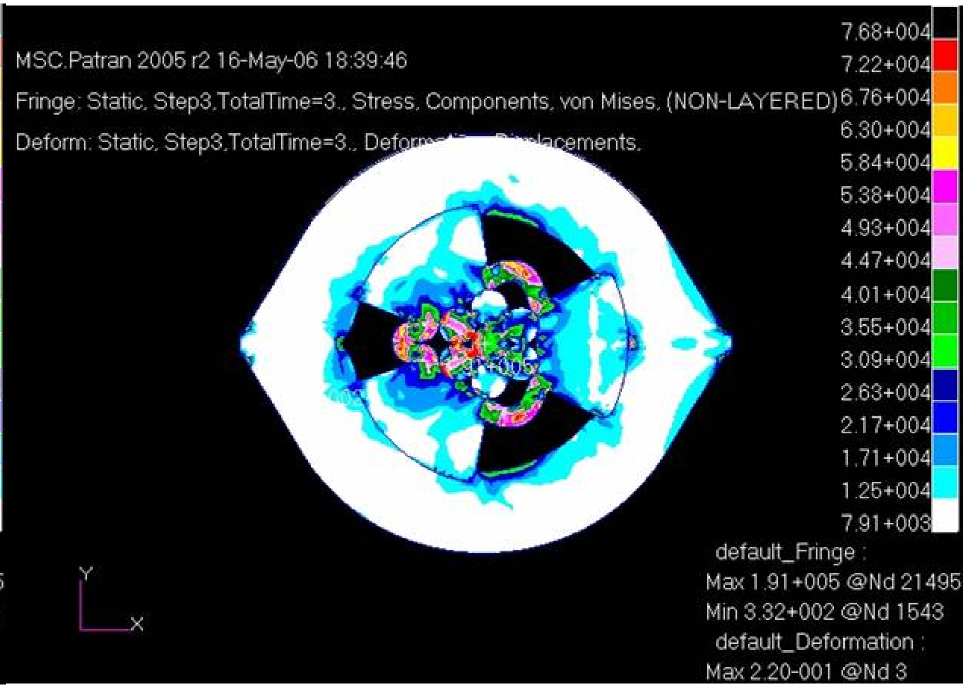
Shear forces at sleeve/conductor interfaces and core-grip/steel-core interface resist pull-out.

FEM Analysis

Relaxation of Clamping Stress

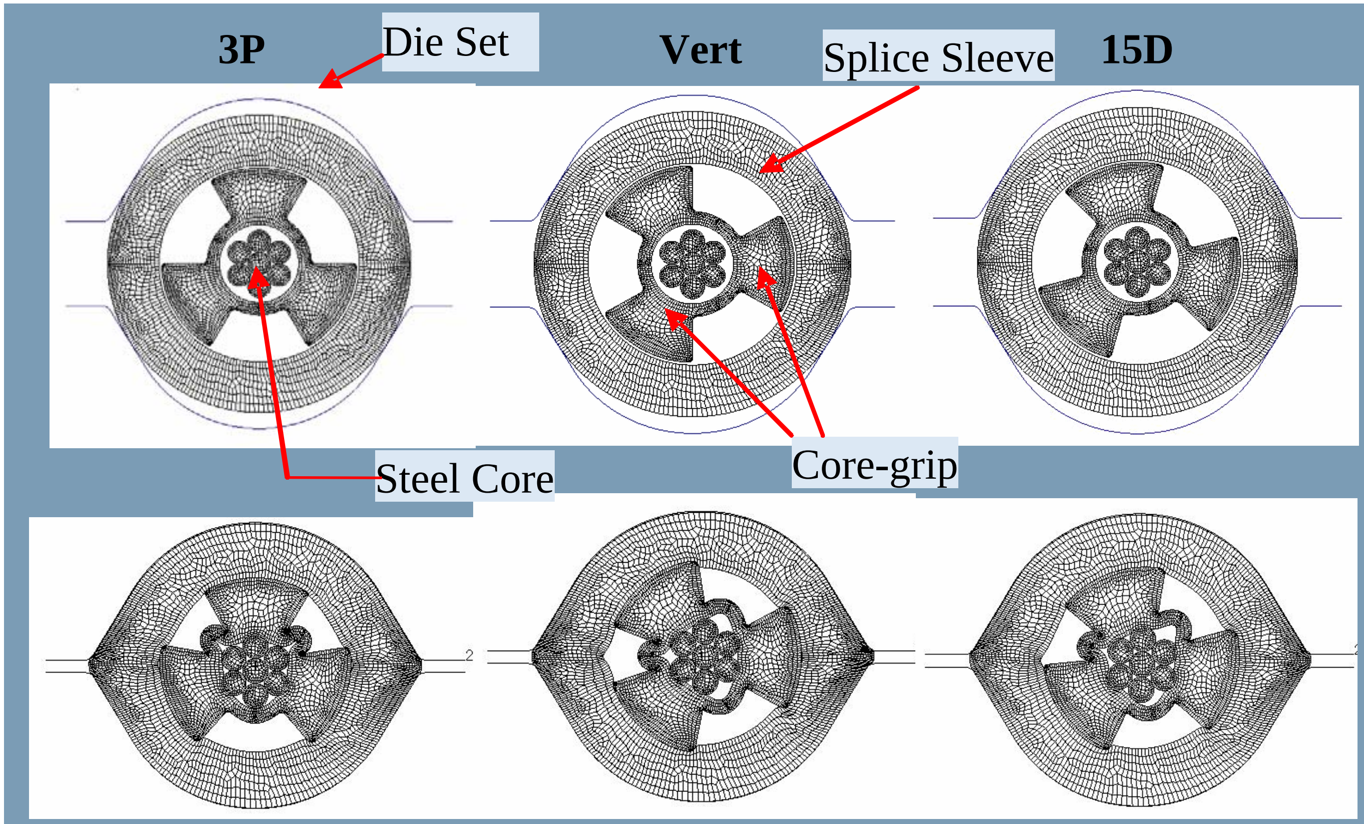


End of crimping process,
before die removal



End of crimping process,
after die removal

Orientation Effect in Core-grip



FEM models for core grip section of Drake splice connector with 6012CD die: (top) before crimping and (bottom) crimped SCC.

FEM Results at Core-grip Section

Core Grip Section/Drake Conductor w/ ALCOA 6012 die (60-ton die)			
Grip position	**3P**	**Vert**	**15D**
Crimp force required per die	**54.6 tons**	**57.5 tons**	**56 tons**
Friction resistance	**36,000 lb**	**32,5000 lb**	**35,6000 lb**

*Steel core wires strength = 18,300 lbs

*Vert core-grip orientation, better chance of failure

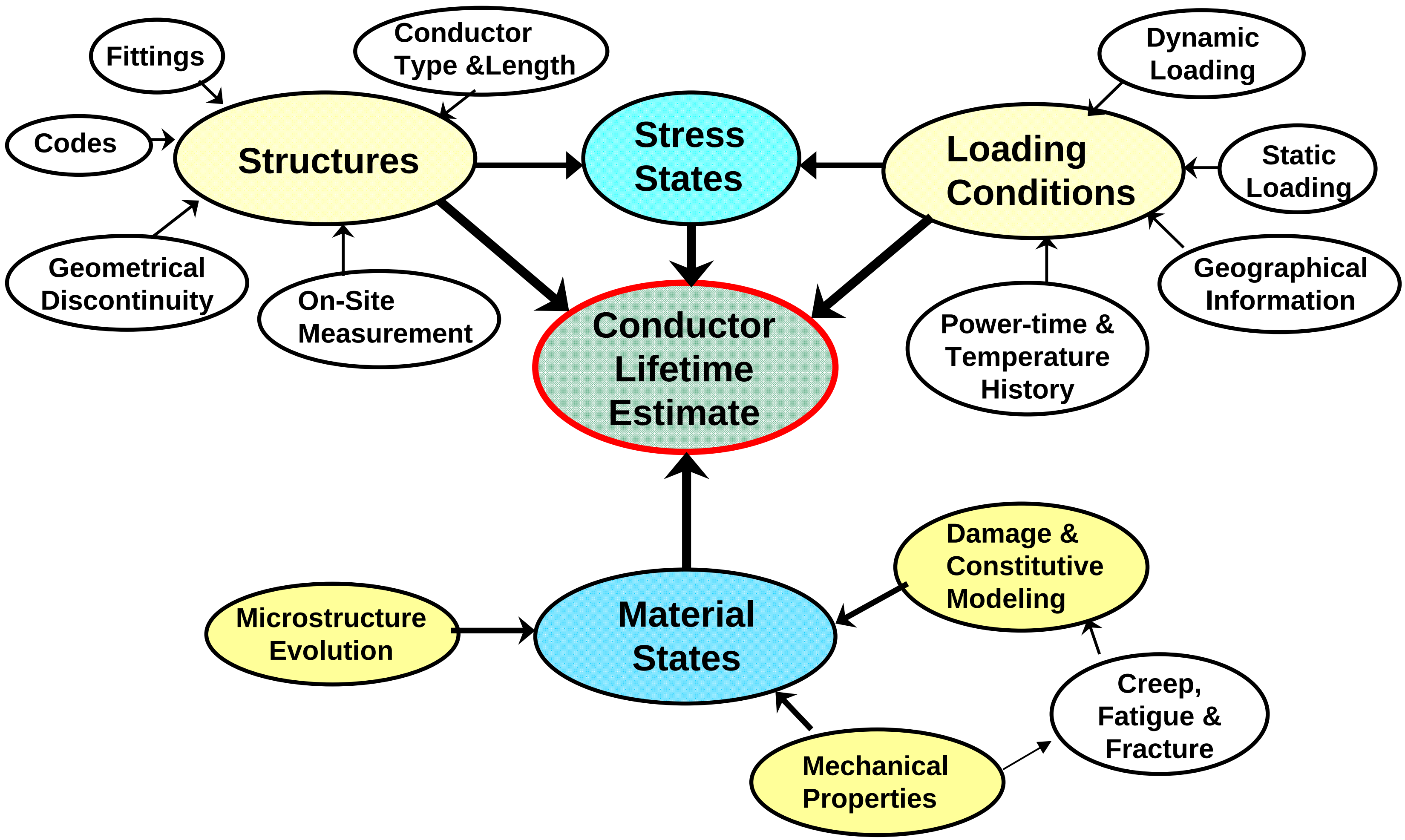
FEM Results at Conductor Section

Conductor Section/Drake Conductor w/ ALCOA 6012 die	
Crimp force required per die	54 tons
Friction resistance	16,092 lb

*Conductor rated breaking strength contributed by conductor = 13,942 lbs

The analyzed clamping strength for a Drake SSC connector was sufficiently large to meet the rated tensile strength, 31,460 lb (1.40E+05 N).

Parameters Involved in Conductor System Lifetime Estimates

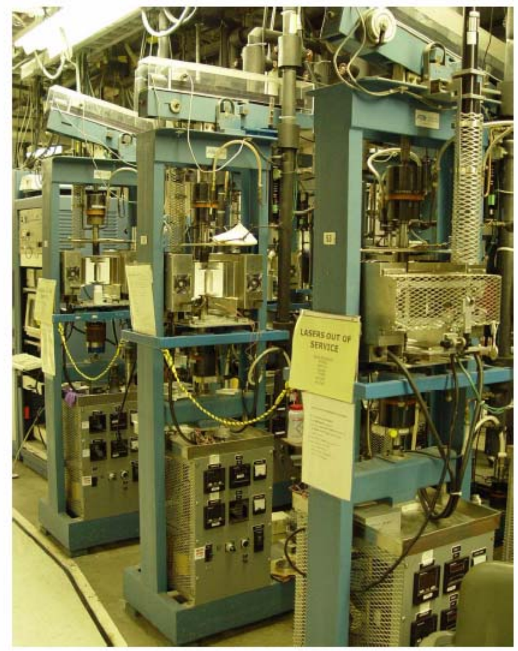


Thermal Mechanical Testing

Materials: 1350-H19 aluminum, 3003-H183 aluminum sleeve, 6061-T6 aluminum core-grip.

Samples machined from core-grip and splice sleeve.

Thermal-mechanical



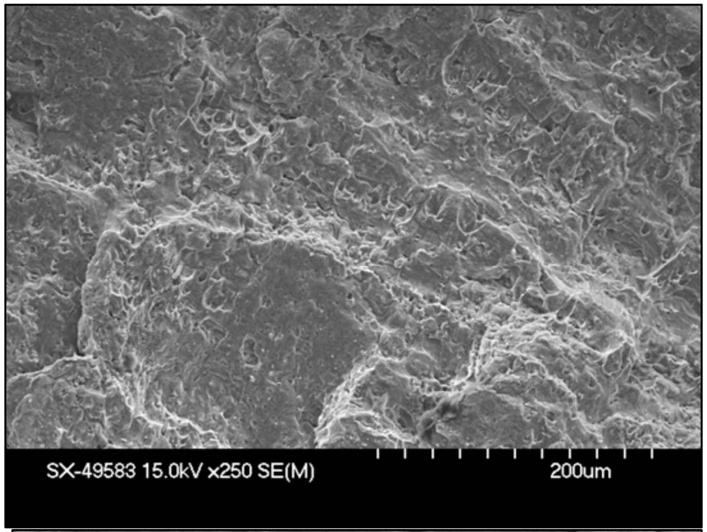
High temperature tensile test with the associated deformation control set-up.

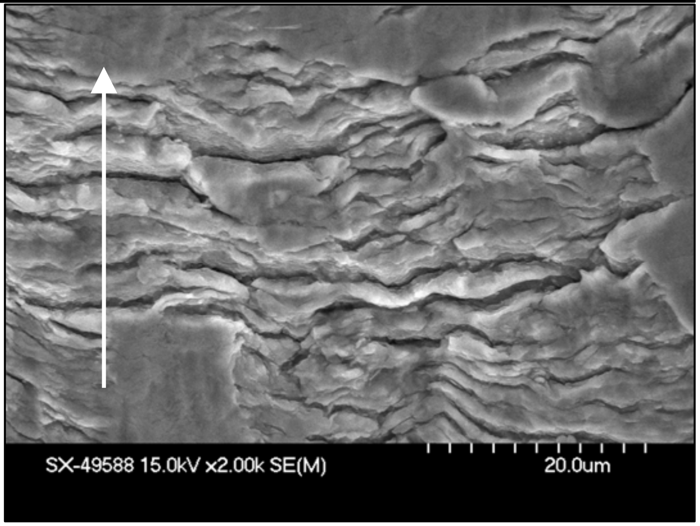
Tensile and Fatigue Test Set-up

Creep tester

Microstructural Evaluation

- Scanning Electronic Microscope used for postmortem examination of fracture tested samples
- The typical fracture surfaces of fatigue fracture sample, made of 1350-H19 aluminum, are shown to the right. The bottom figure reveals the typical fatigue striation pattern.

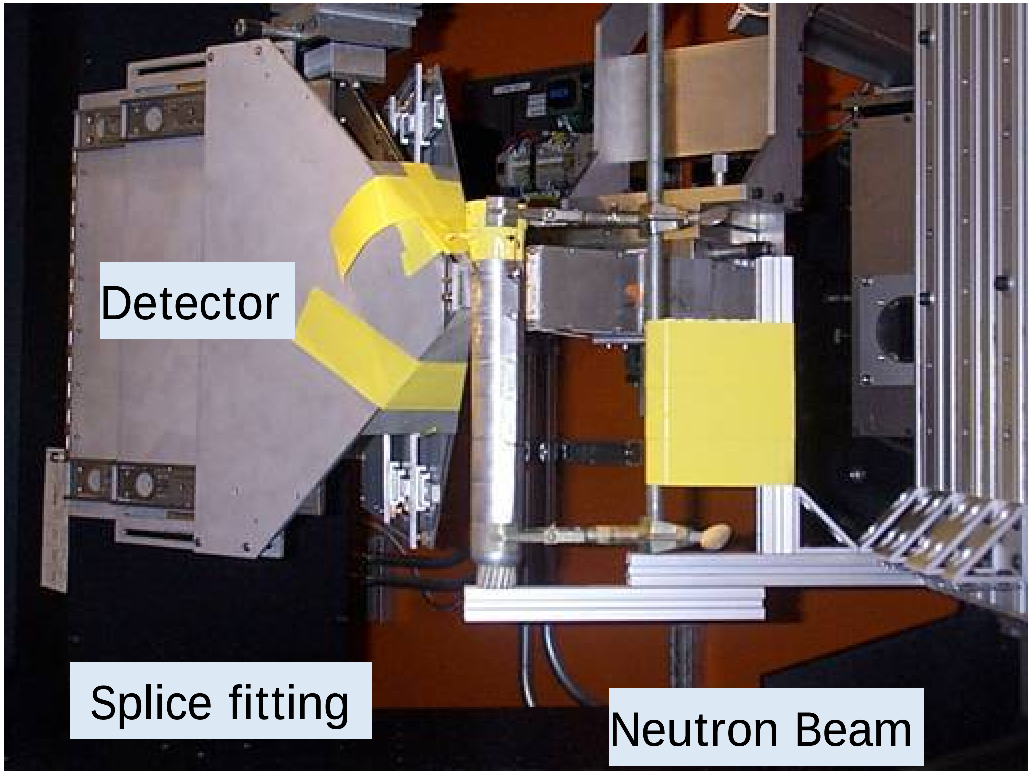




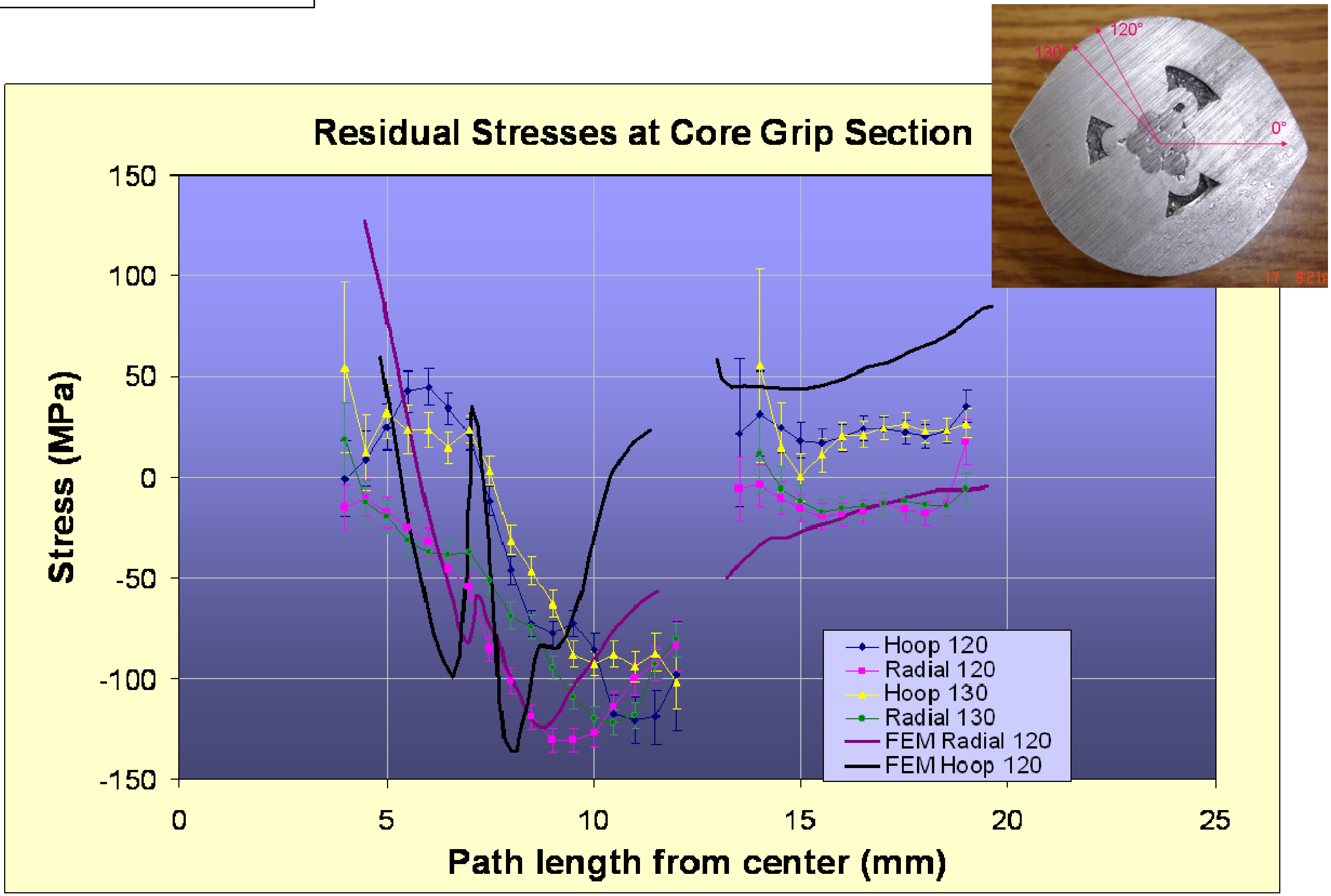
In-situ NDE Residual Stress Verification - neutron scattering technique

Neutron diffraction measurements were performed at the High Flux Isotope Nuclear Reactor, Neutron Residual Stress Mapping Facility (NRSF2)

- Residual strains in radial (normal) direction were measured at 120° (130°) from the principal axis of the connectors.
- Radial and hoop strain measured at core grip section



Confirmatory Evaluation



Summary

- Splice-conductor interface is the most critical issue to be addressed in order to predict the reliability of transmission lines
- Accumulated damage is considerably higher in SSC than TSC connector fitting.
- Unique approach has been developed to accurately estimate the remaining life of conductor systems.
- FEM results match the SSC forming, and also indicate the geometry and orientation effect of SSC forming.
- In-situ residual stress measurements confirm the FEM results.
- Degradation of residual stress provides estimate of SSC lifetime.
- Thermal mechanical testing provides basis to characterize the fatigue and creep associated damage.

Next Steps

- Complete ACSR Analysis
- Initiate ACSS Analysis
- Analyze Two-stage Connector Fitting
- Model other HTLS Conductor and Connector systems
- Develop Novel Connector Designs

Acknowledgments

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