Sag-tension Calculations

A Tutorial Developed for the IEEE TP&C Line Design Subcommittee

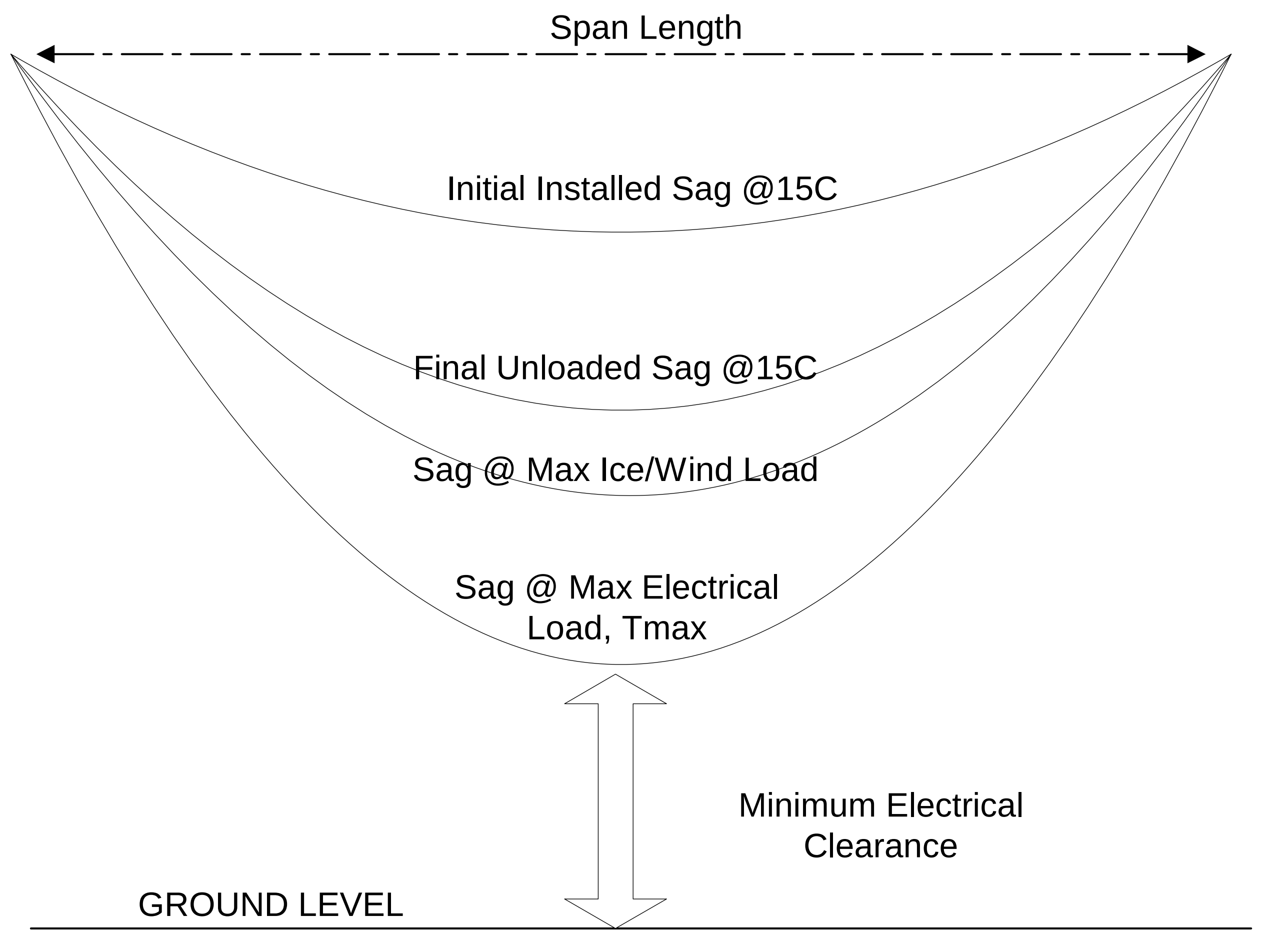
Based on a CIGRE WG B2.12 Technical Brochure under Development

Dale Douglass   June, 2005

CIGRE & IEEE Websites

- CIGRE WG B2.12 – Electrical Effects in Lines
  http://www.geocities.com/wg_12/index.htm
  - Technical Brochure 244 – Conductors for Uprating of Existing Lines
  - Probabilistic Ratings & Joints
- IEEE Towers Poles & Conductors
  http://www.geocities.com/ieee_tpc/index.htm
  - IEEE Standard 738 – 1993
  - Panel Sessions Jan 28 (Las Vegas) June 4 (SF)

Sag-tension Envelope



SAG10 Calculation Table

Design Points					Final			Initial		
Temp F	Ice in	Wind psf	K lb/f	Weight lb/f	Sag ft	Tension lb	RTS %	Sag ft	Tension lb	RTS %
0.	.50	4.00	.30	2.509	23.91	13142.	41.7	23.03	13647.	43.3
						7064.A			7718.A	
						6078.S			5929.S	
32.	1.00	.00	.00	3.715	29.08	16026.	50.9	29.08	16026.	50.9
						8543.A			8543.A	
						7483.S			7483.S	
-20.	.00	.00	.00	1.094	16.04	8532.	27.1	13.55	10103.	32.1
						4361.A			6269.A	
						4171.S			3834.S	
0.	.00	.00	.00	1.094	17.39	7875.	25.0*	14.43	9485.	30.1
						3727.A			5820.A	
						4148.S			3665.S	
60.	.00	.00	.00	1.094	21.48	6379.	20.3	17.45	7847.	24.9
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212.	.00	.00	.00	1.094	29.71	4619.	14.7	26.07	5259.	16.7
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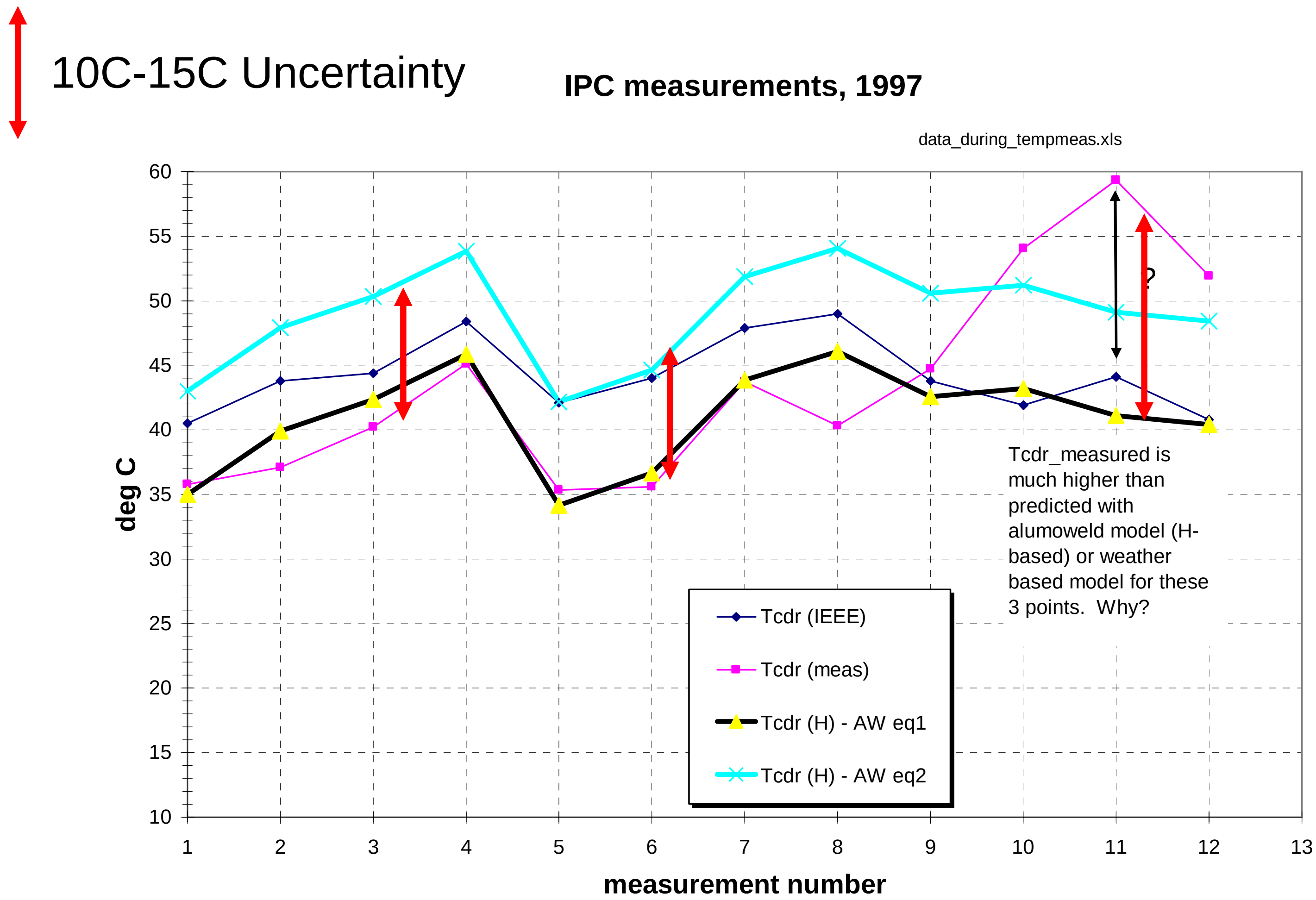
						-94.A			610.A	
						4325.S			3827.S	

* Design Condition

From Alcoa-Fujikura SAG10 program

A Bit of Perspective



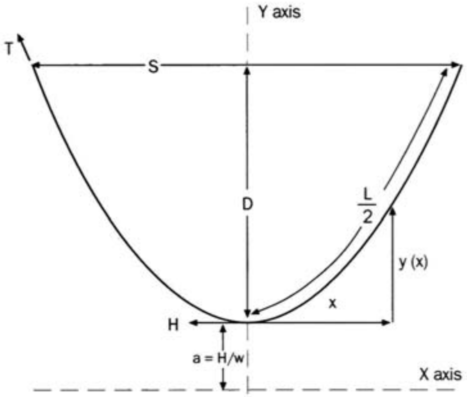
Some Questions

- Why can we do calculations for a single span and use for an entire line section?
- How are initial and final conditions defined?
- Why not run the maximum tension to 60% as the NESC Code allows?
- Why do I see negative tensions (compression) in aluminum at high temperature?

The Catenary Curve

- HyperbolicFunctions & Parabolas
- Sag vs weight & tension
- Length between supports
- What is Slack?
- What if the span isn't level?

The Catenary – Level Span



$$y(x) = \frac{H}{w} \cdot \left[\cosh\left(\frac{w \cdot x}{H} \right) - 1 \right] \cong \frac{w \cdot x^2}{2 \cdot H}$$

$$D = \frac{H}{w} \cdot \left\{ \cosh\left(\frac{w \cdot S}{2 \cdot H} \right) - 1 \right\} \cong \frac{w \cdot S^2}{8 \cdot H}$$

$$L = \left(\frac{2H}{w} \right) sinh\left(\frac{Sw}{2H} \right) \cong S\left(1 + \frac{S^2 w^2}{24 H^2} \right)$$

Catenary Sample Calcs for Drake ACSR

- 1.094 lbs/ft Bare Weight
- 31,500 lbs Rated Breaking Strength
- 600 ft span

$$D = \frac{6300}{1.094}\left[\cosh\left(\frac{1.094 \cdot 600}{2 \cdot 6300}\right)\right] = 7.831\ ft\ (2.387\ m)$$

$$L = \frac{2*6300}{1.094}\sinh\left(\frac{1.094*600}{2*6300}\right) = 600.272\ ft\ \ (182.963\, m)$$

Catenary Calculations

What Happens when the weight of the conductor changes

Ice & Wind Loading

- Radial ice (Quebec)
- Wind Pressure (Florida)
- Wind & Ice Combined (Illinois)

What about changes in loading?

NESC Loading District				
	Heavy	***Medium***	***Light***	***Extreme wind loading***
Radial thickness of ice (in) (mm)	0.50 12.5	0.25 6.5	0 0	0 0
Horizontal wind pressure (lb/ft^2) (Pa)	4 190	4 190	9 430	See Fig 2-4
Temperature (^oF) (^oC)	0 -20	+15 -10	+30 -1	+60 +15
NESC safety factors to be added to the resultant (lb/ft) (N/m)	0.30 4.40	0.20 2.50	0.05 0.70	0.0 0.0

Iced Conductor Weight

$$w_{ice} = 1.244t\,(D_c + t)$$

ACSR Conductor	D_c, in	w_{bare}, lb/ft	w_{ice}, lb/ft	$\frac{w_{bare} + w_{ice}}{w_{bare}}$
#1/0 AWG -6/1 “Raven”	0.398	0.1452	0.559	4.8
477 kcmil-26/7 “Hawk”	0.858	0.6570	0.845	2.3
1590 kcmil-54/19 “Falcon"	1.545	2.044	1.272	1.6

What happens when the conductor weight changes?

- Bare weight of Drake ACSR is 1.094 lb/ft
- Iced weight is:
  - 1.094 + 1.244*1.0*(1.108+1.0) = 3.60 lb/ft
- Tension increases by a factor of 3.6 unless the length of the conductor changes.

SAG10 Calculation Table

Design Points					Final			Initial		
Temp	Ice	Wind	K	Weight	Sag	Tension	RTS	Sag	Tension	RTS
F	in	psf	lb/f	lb/f	ft	lb	%	ft	lb	%
0.	.50	4.00	.30	2.509	23.91	13142.	41.7	23.03	13647.	43.3
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* Design Condition

From Alcoa-Fujikura SAG10 program

Conductor tension limits

- Avoiding tension failure (Safety factor)
- Limiting vibration (H/w, %RBS)
- Designing with less sag

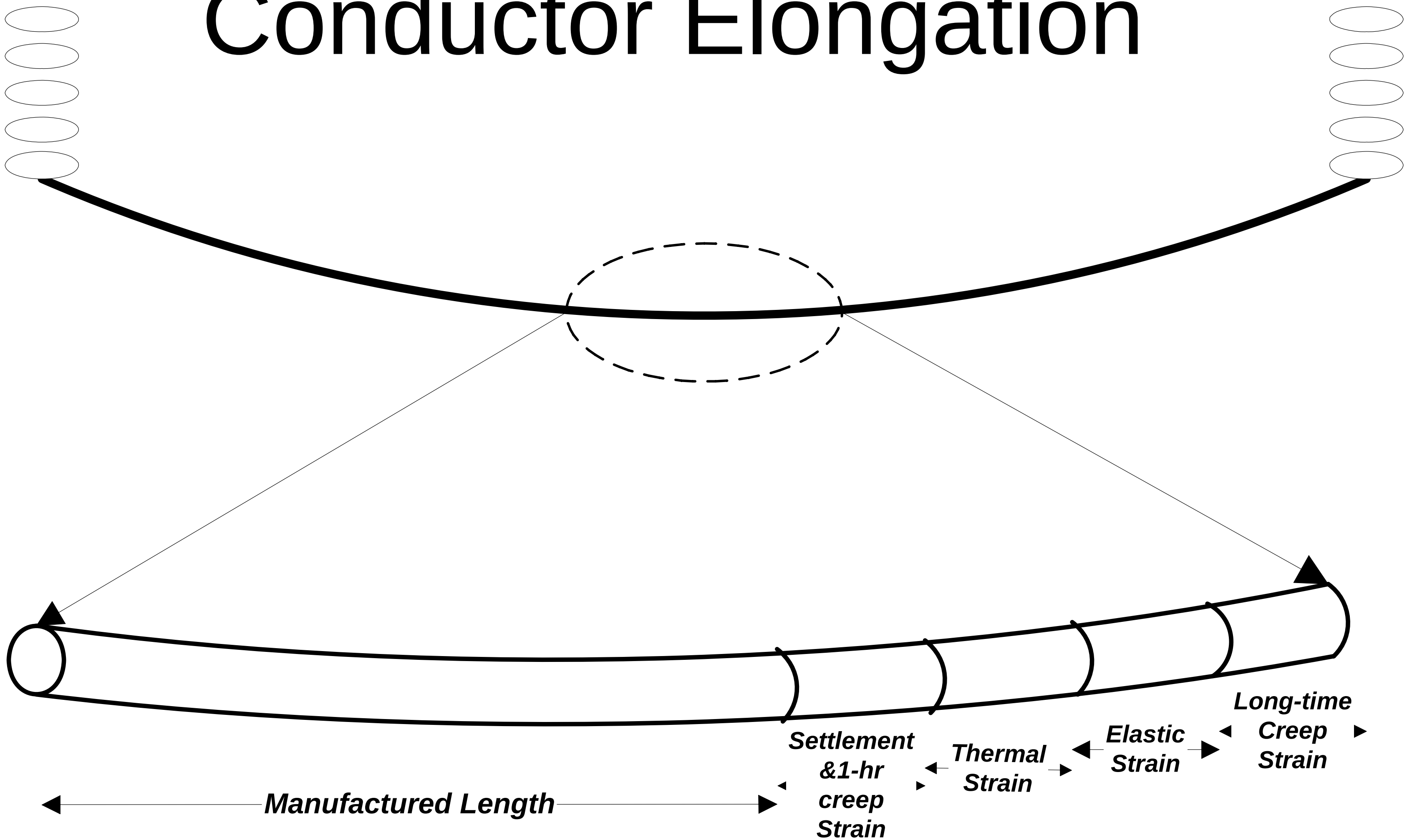
Tension Limits and Sag

Tension at 15C unloaded initial - %RTS	Tension at max ice and wind load - %RTS	Tension at max ice and wind load - kN	Initial Sag at 100C - meters	Final Sag at 100C - meters
10	22.6	31.6	14.6	14.6
15	31.7	44.4	10.9	11.0
20	38.4	53.8	9.0	9.4
25	43.5	61.0	7.8	8.4

Conductor Elongation

- Elastic elongation (springs)
- Settlement & Short-term creep (before sagging)
- Thermal elongation
- Long term creep (After sagging, over the life of the line)

Conductor Elongation

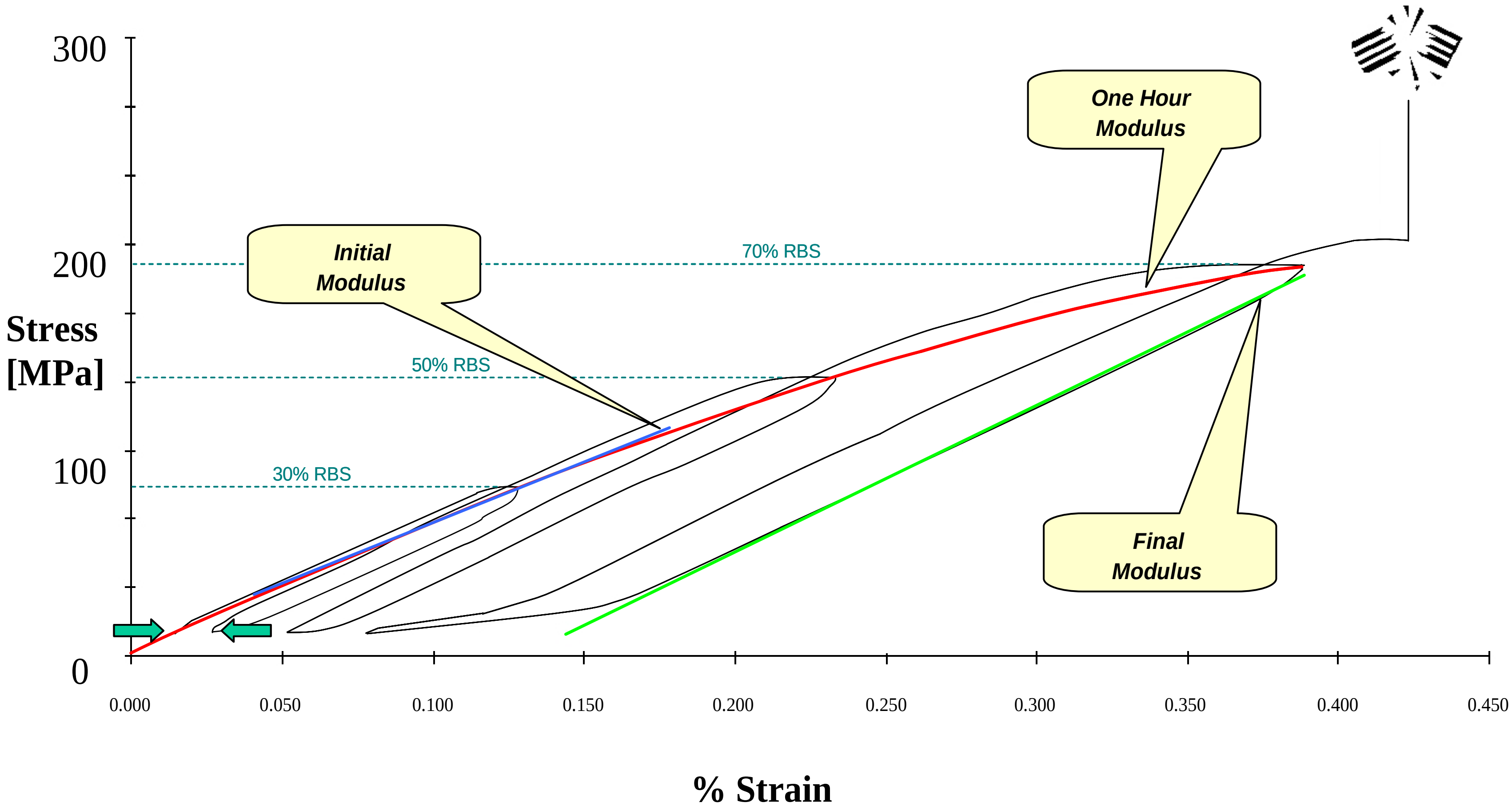


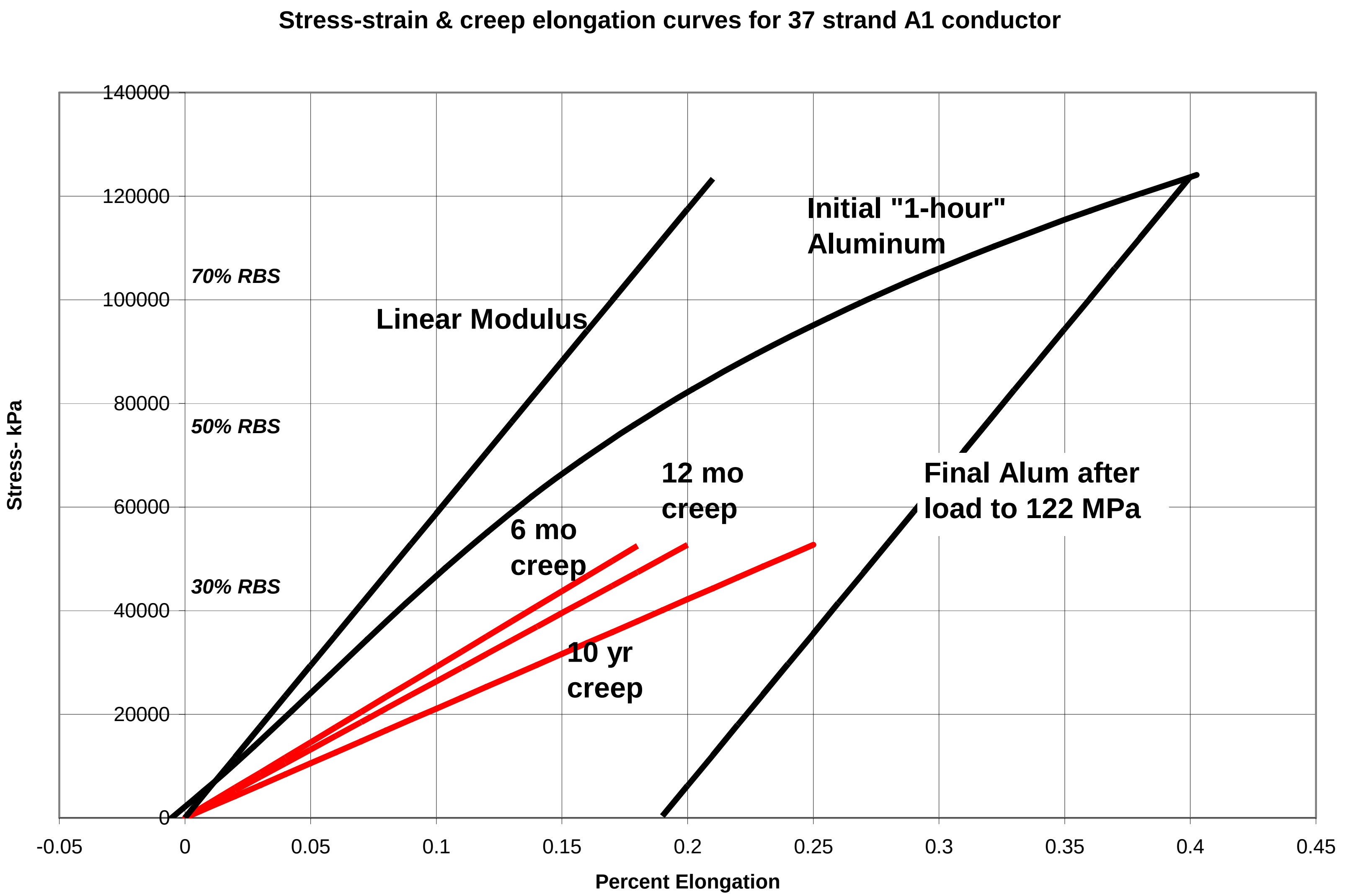
Thermal Elongation

	International Annealed Copper Standard	Commercial Hard-Drawn Copper Wire	Standard 1350-H19 Aluminum Wire	Galv. Steel Core Wire
Conductivity, % IACS @ 20ºC	100.00	97.00	61.2	8.0
Coefficient of Linear Expansion 10^{-6} per ºF	9.4	9.4	12.8	6.4

Courtesy of Southwire Corp.

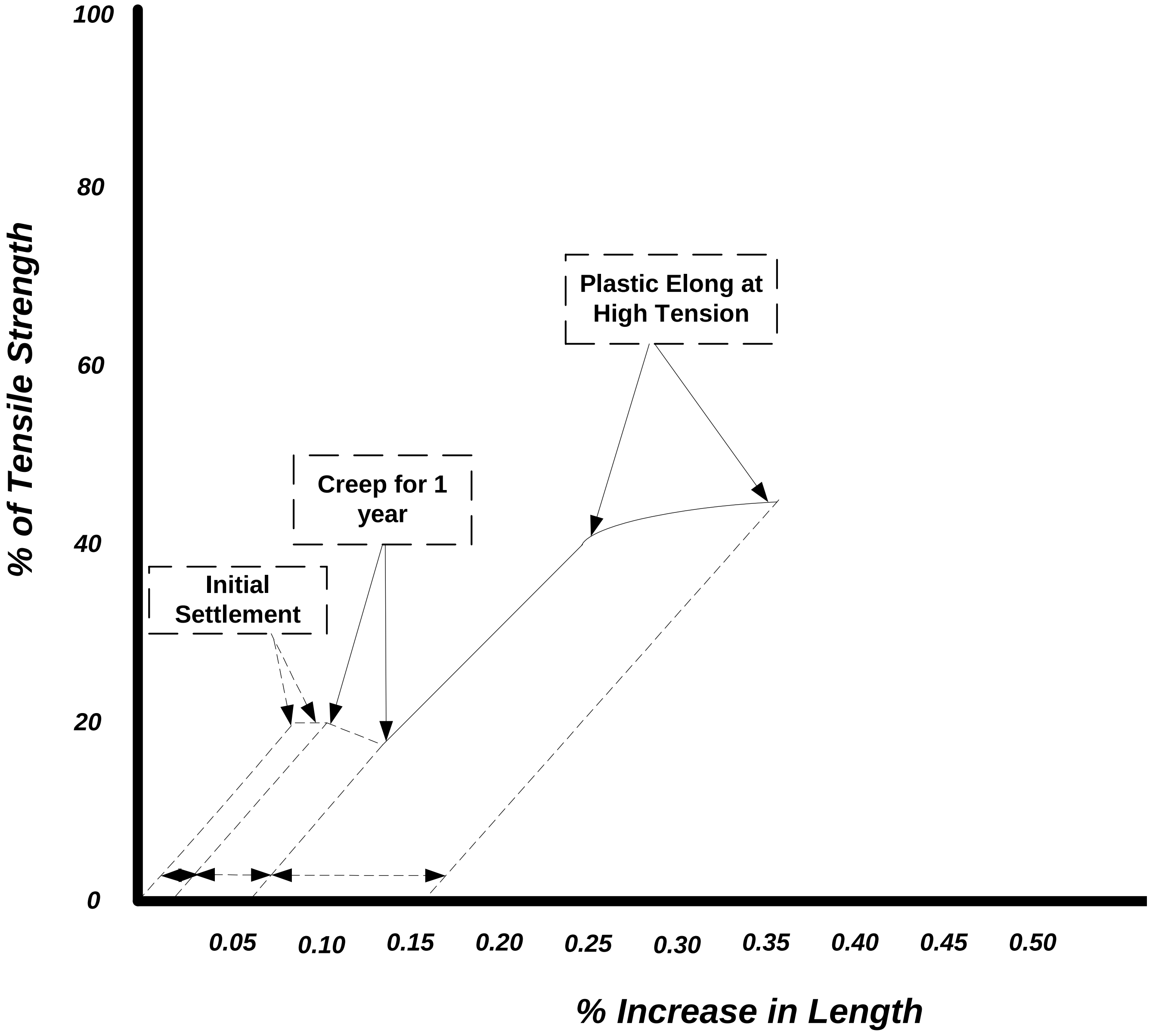
Stress-Strain Test




Stress-strain & creep elongation curves for 37 strand A1 conductor
140000
120000
100000
80000
60000
40000
20000
0
-0.05
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
Stress- kPa
Percent Elongation
70% RBS
50% RBS
30% RBS
Linear Modulus
Initial "1-hour" Aluminum
Final Alum after load to 122 MPa
6 mo creep
12 mo creep
10 yr creep

Conductor Elongation

- Elastic elongation (reversible)
- Settlement & Short-term creep (permanent)
- Thermal elongation (reversible)
- Long term creep (permanent after years or high loads)


100
80
60
40
20
0
% of Tensile Strength
Plastic Elong at High Tension
Creep for 1 year
Initial Settlement
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
% Increase in Length

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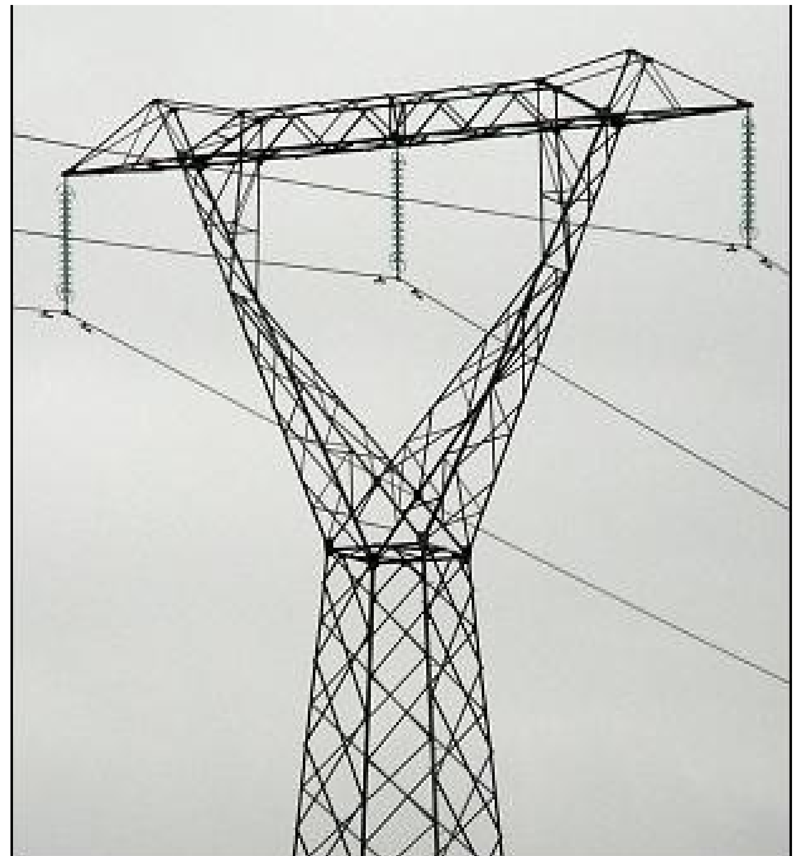
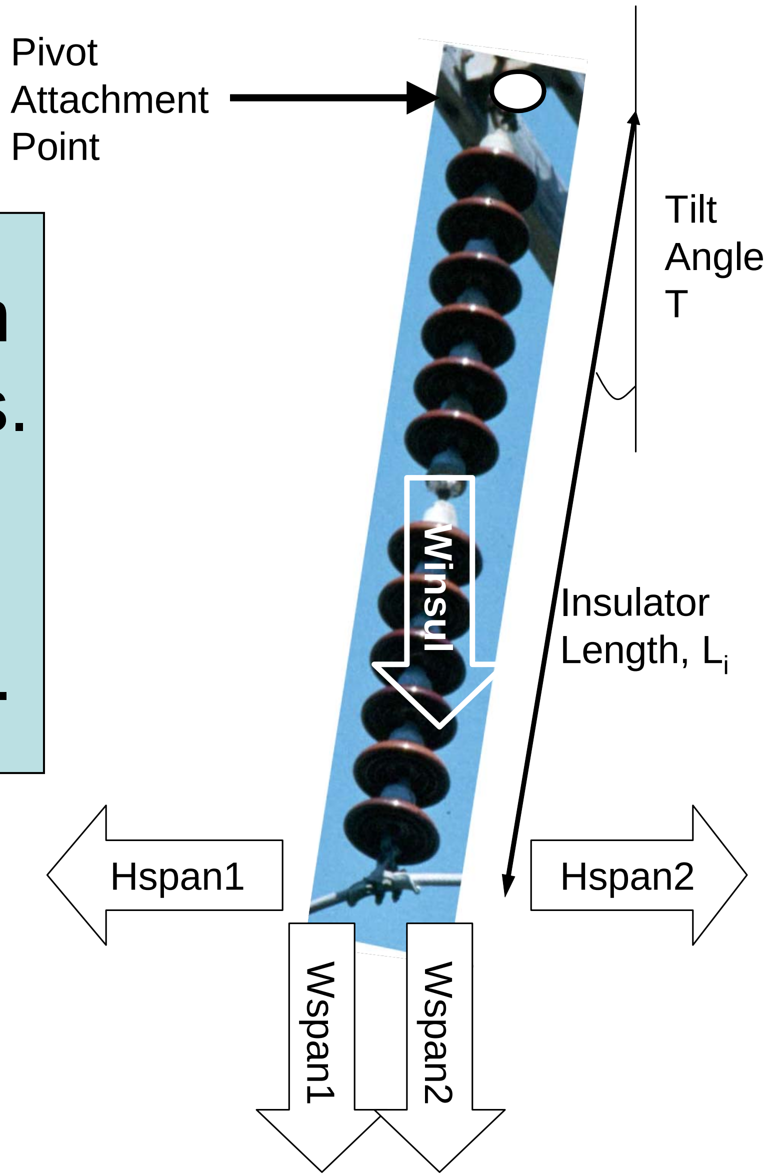
What is a ruling span?



Tension equalization at suspension points.

The basis of the ruling span concept.



The “Ruling Span”

$$RS = \sqrt{\frac{S_1^3 + S_2^3 + ---- + S_n^3}{S_1 + S_2 + ---- + S_n}}$$

$$RS = \sqrt{\frac{600^3 + 900^3 + 600^3}{600 + 900 + 600}} = 745\,ft$$

- Based on Tension equalization
- Used for Stringing sags
  - Sag = (w/8H)*S^2

Sag-tension Calculations - Deliverables

- Maximum sag so that clearance to ground and other conductors can be maintained.
- Maximum tension so that structures can be designed to withstand it.
- Minimum sag to control structure uplift problems.
- H/w during “coldest month” to limit aeolian vibration.

Summary of Some Key Points

- Tension equalization between suspension spans allows use of the ruling span
- Initial and final conditions occur at sagging and after high loads and multiple years
- For large conductors, max tension is typically below 60% in order to limit wind vibration & uplift
- Negative tensions (compression) in aluminum occur at high temperature for ACSR because of the 2:1 diff in thermal elongation between alum & steel

General Sag-Ten References

- Aluminum Association Aluminum Electrical Conductor Handbook Publication No. ECH-56"
- Southwire Company "Overhead Conductor Manual“
- Barrett, JS, Dutta S., and Nigol, O., *A New Computer Model of A1/S1A (ACSR) Conductors*, IEEE Trans., Vol. PAS-102, No. 3, March 1983, pp 614-621.
- Varney T., Aluminum Company of America, “Graphic Method for Sag Tension Calculations for A1/S1A (ACSR) and Other Conductors.”, Pittsburg, 1927
- Winkelman, P.F., “Sag-Tension Computations and Field Measurements of Bonneville Power Administration, AIEE Paper 59-900, June 1959.
- IEEE Working Group, “Limitations of the Ruling Span Method for Overhead Line Conductors at High Operating Temperatures”. Report of IEEE WG on Thermal Aspects of Conductors, IEEE WPM 1998, Tampa, FL, Feb. 3, 1998
- Thayer, E.S., “Computing tensions in transmission lines”, Electrical World, Vol.84, no.2, July 12, 1924
- Aluminum Association, “Stress-Strain-Creep Curves for Aluminum Overhead Electrical Conductors,” Published 7/15/74.
- Barrett, JS, and Nigol, O., *Characteristics of A1/S1A (ACSR) Conductors as High Temperatures and Stresses*, IEEE Trans., Vol. PAS-100, No. 2, February 1981, pp 485-493
- Electrical Technical Committee of the Aluminum Association, “A Method of Stress-Strain Testing of Aluminum Conductor and ACSR” and “A Test Method for Determining the Long Time Tensile Creep of Aluminum Conductors in Overhead Lines”, January, 1999, The aluminum Association, Washington, DC 20006, USA.
- Harvey, JR and Larson RE. *Use of Elevated Temperature Creep Data in Sag-Tension Calculations*. IEEE Trans., Vol. PAS-89, No. 3, pp. 380-386, March 1970
- Rawlins, C.B., “Some Effects of Mill Practice on the Stress-Strain Behaviour of ACSR”, IEEE WPM 1998, Tampa, FL, Feb. 1998.

The End

A Sag-tension Tutorial

Prepared for the IEEE TP&C Subcommittee by Dale Douglass