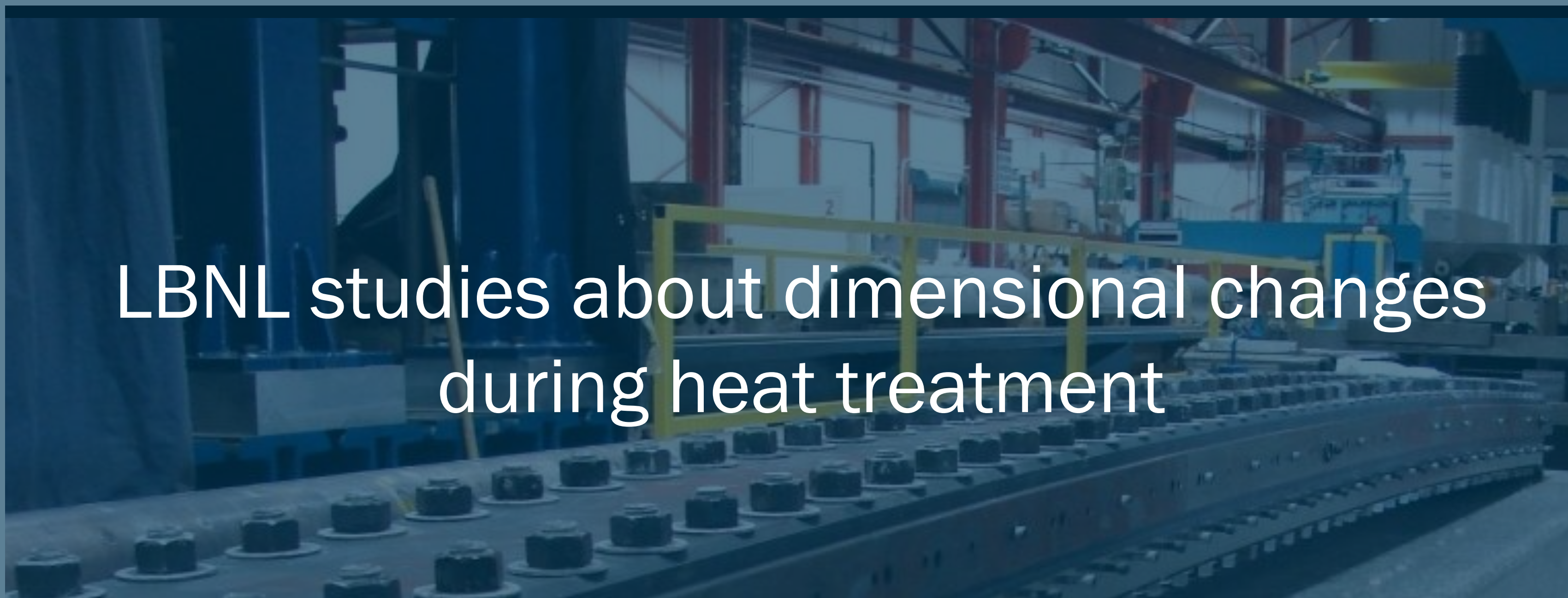
U.S. MAGNET DEVELOPMENT PROGRAM



LBNL studies about dimensional changes during heat treatment

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Thanks to Daniel Dietderich, Helene Felice, Etienne Rochepault, Ian Pong, Charlie Sanabria, Jyothi Krishnan

Outline

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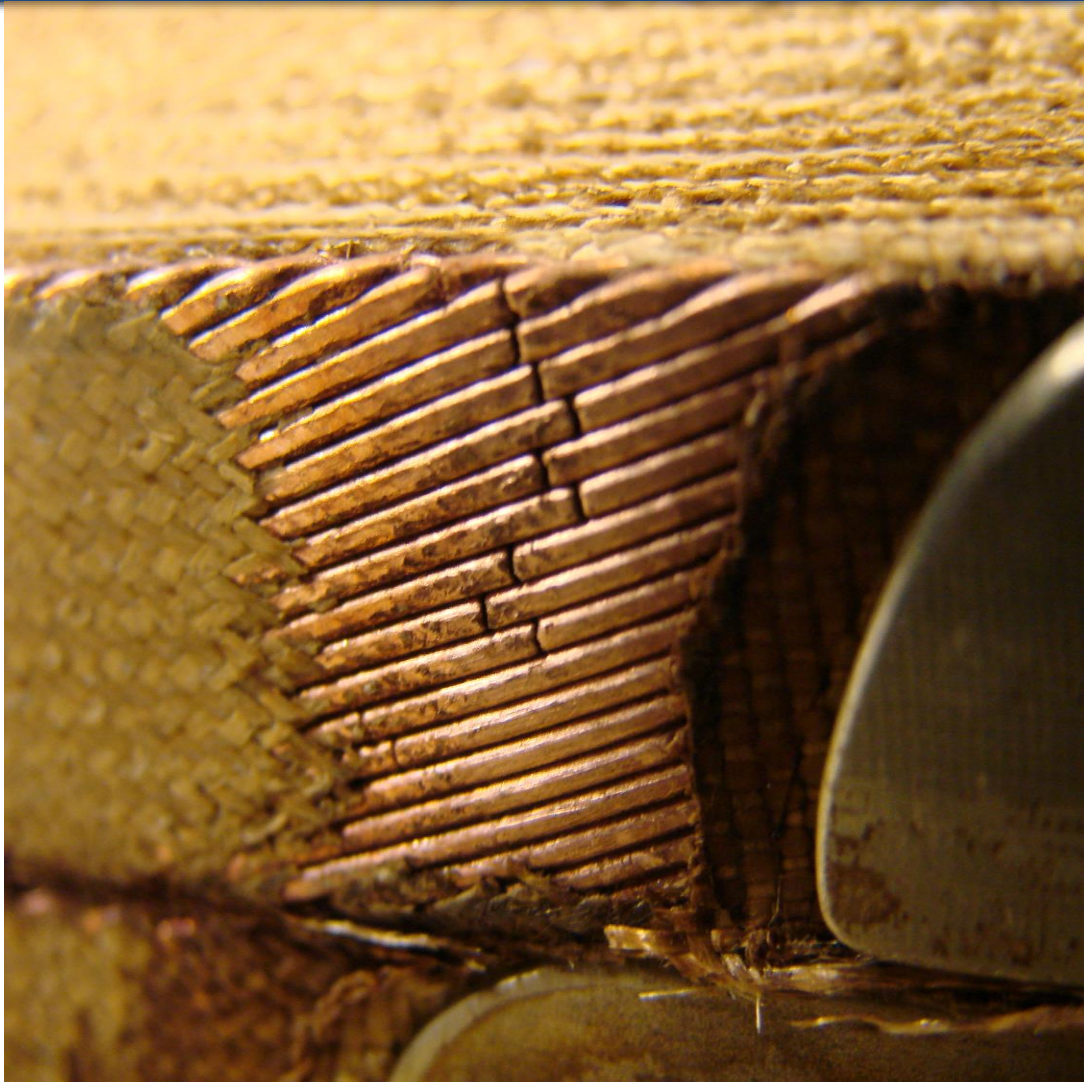
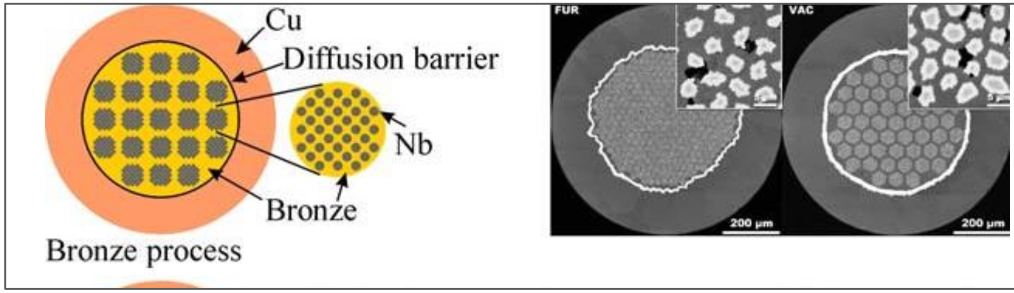
- A basic review of the phases in RRP® Nb_3Sn heat treatment
- First studies of heat treatment impact on conductor length
- Extension of heat treatment dimensional changes to cables
- Impact of confinement on dimensional changes
- Some thoughts on out-standing questions



The complexity of modern Nb_3Sn superconductors is well known

Godeke thesis



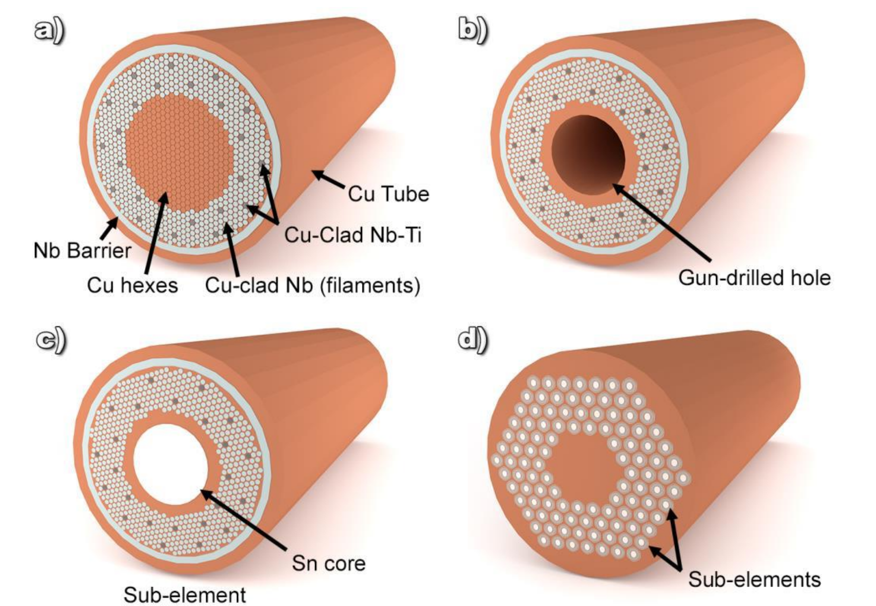


Figure 21 (a) A sketch of stacked Cu hexes and Cu-clad Nb rods-in-hex surrounded by a Nb tube and a Cu tube. Notice a few Cu-clad Nb-Ti rods are used for doping purposes. (b) A sketch of the previous stack after extrusion to bond the components, and after gun-drilling the center in order to insert a Sn rod. (c) The sub-element complete once the Sn rod was inserted and the components bonded via cold-drawing. (d) A sketch of a fully processed RRP® wire after the sub-elements have been restacked and a Cu jacket added

Sanabria thesis

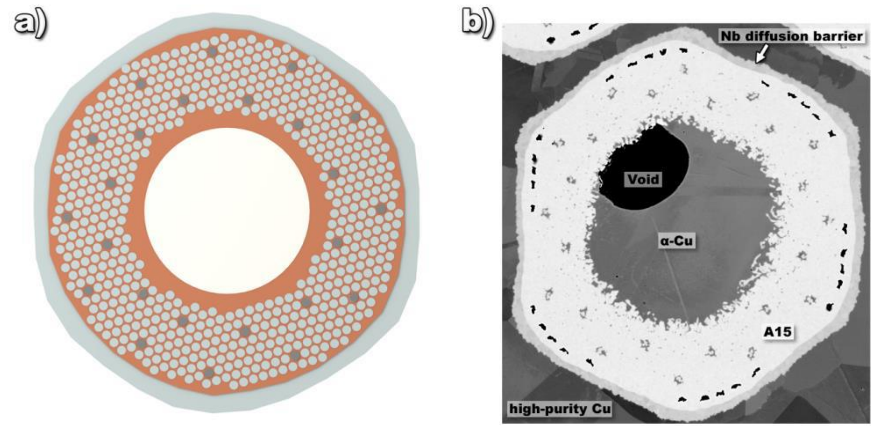
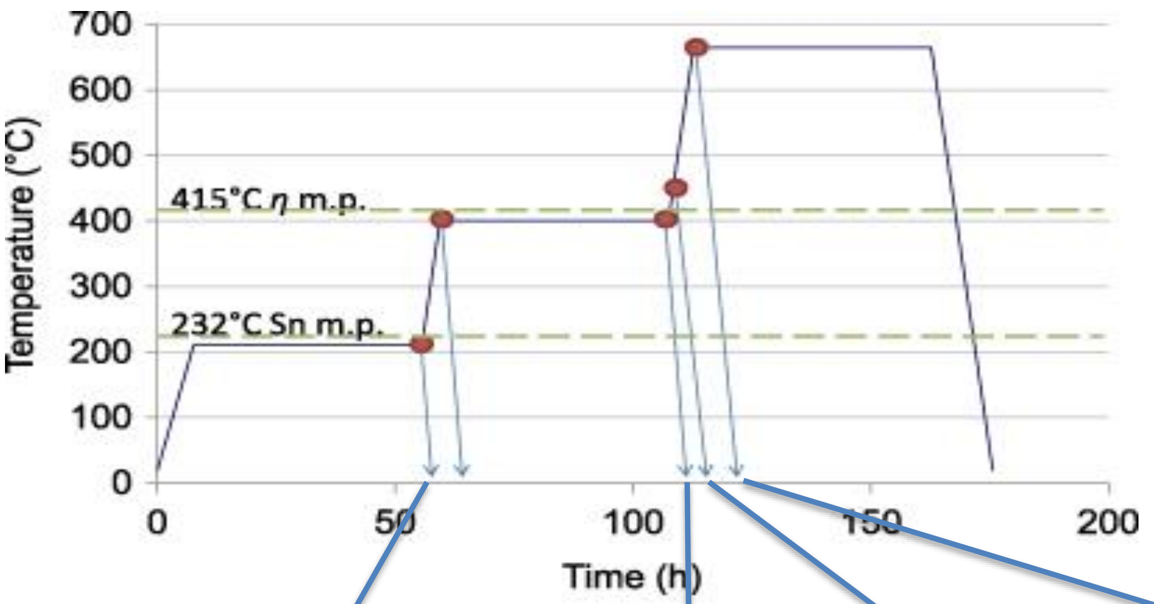


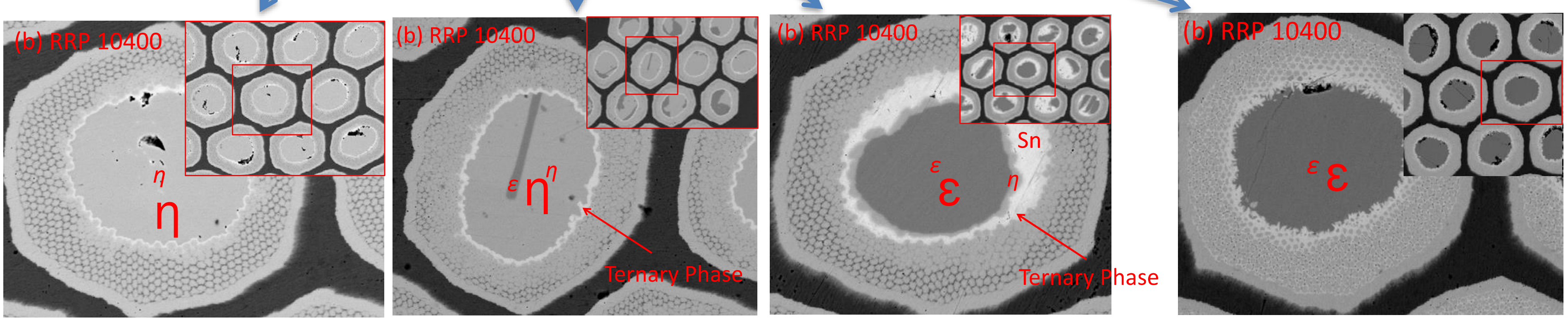
Figure 44 (a) A sketch of a standard sub-element cross section. (b) a fully reacted RRP® sub-element showing the monolithic Nb_3Sn ring that is formed after reaction.

As the superconductor undergoes heat treatment, a number of processes occur that can impact the mechanical behavior of the wire



Pong et al. SUST 2013

Nausite formation



A detailed understanding of the chemical processes and associated mechanics occurring during heat treatment remains elusive

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DIMENSIONAL CHANGES OF Nb_3Sn, Nb_3Al AND $Bi_2Sr_2CaCu_2O_8$ CONDUCTORS DURING HEAT TREATMENT AND THEIR IMPLICATION FOR COIL DESIGN

ICMC '97

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Change in dL/dT due to different volume fraction after formation of intermetallics

Expansions with composite nature; Nb and Cu mix. Length increases with temperature similar to Cu

Formation of Cu-Sn phases results in density change – no increase in length, or even contraction

Conductor elongates with temperature

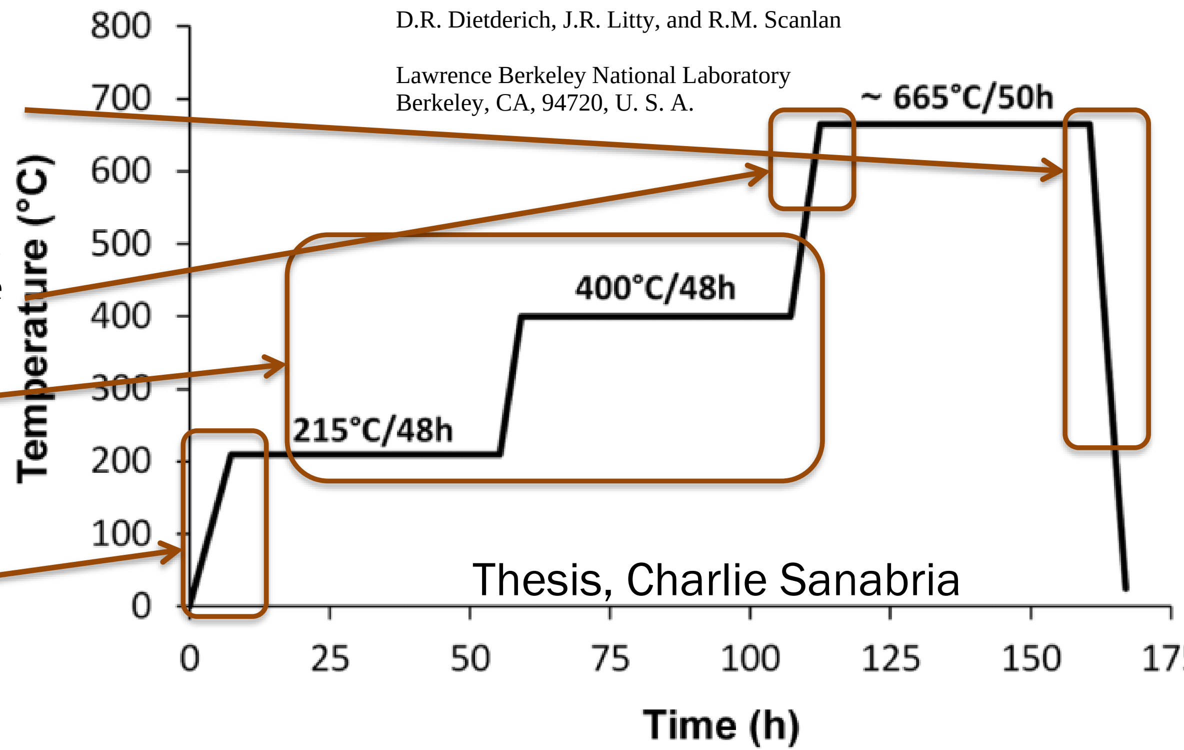
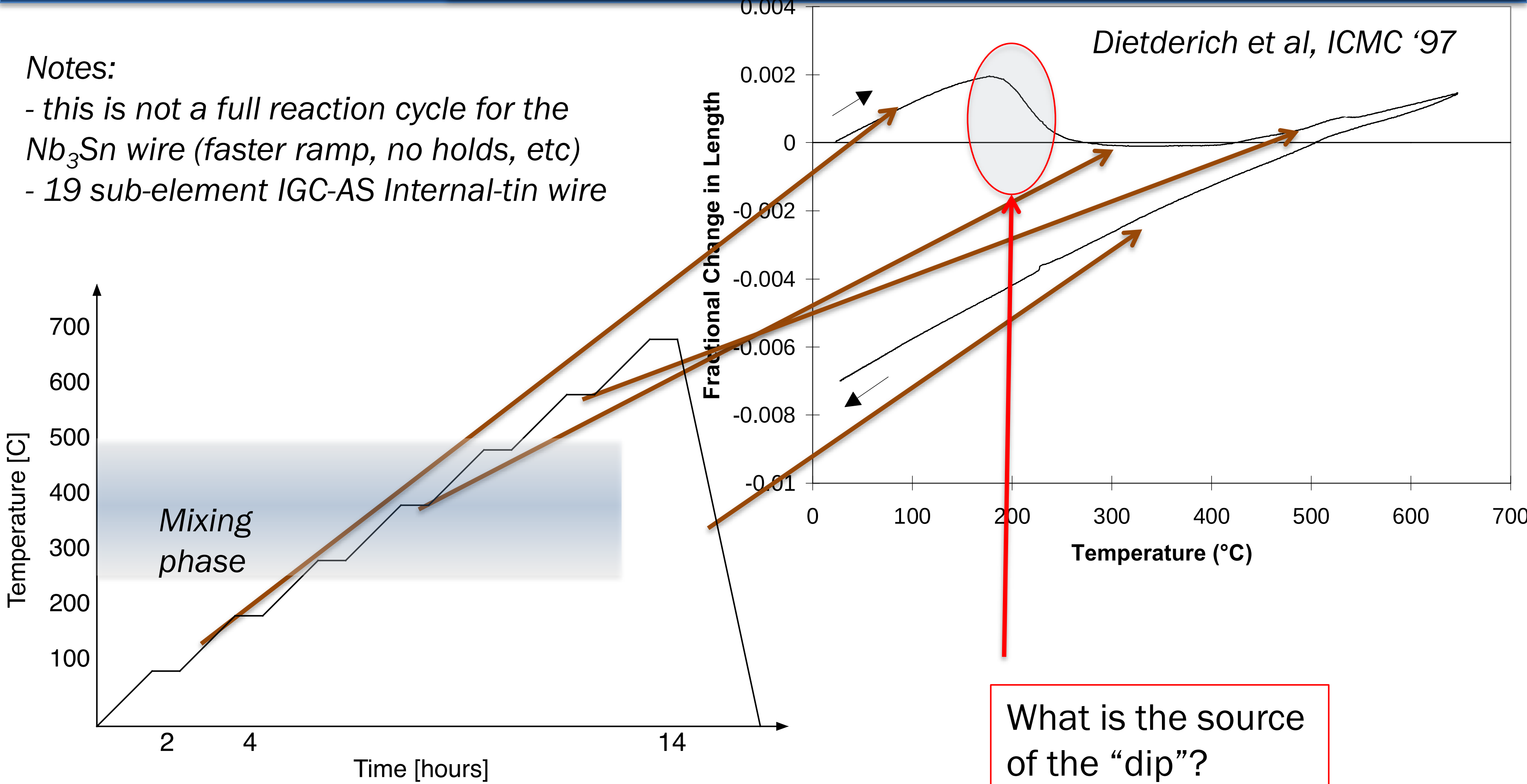


Figure 42 The standard heat treatment for RRP® wires since 2005.

Early dilatometry measurements provide some insight into mechanics of wires during reaction

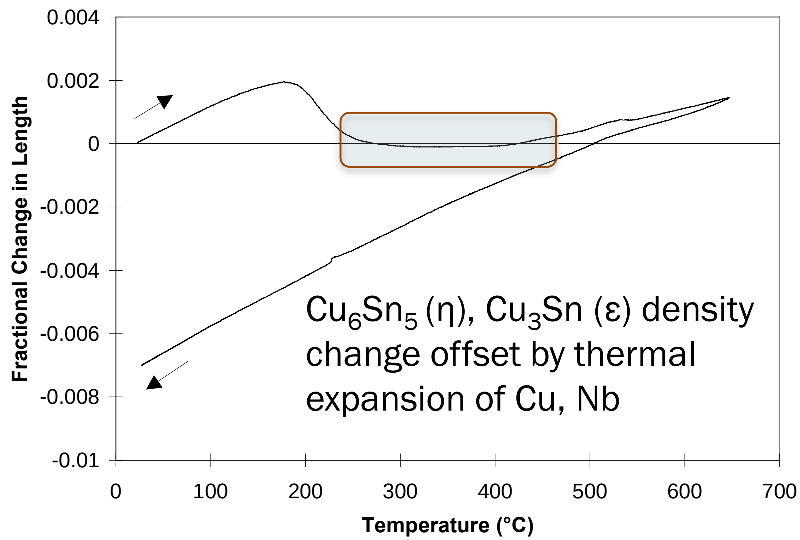
Notes:
- this is not a full reaction cycle for the Nb_3Sn wire (faster ramp, no holds, etc)
- 19 sub-element IGC-AS Internal-tin wire



What is the source of the "dip"?

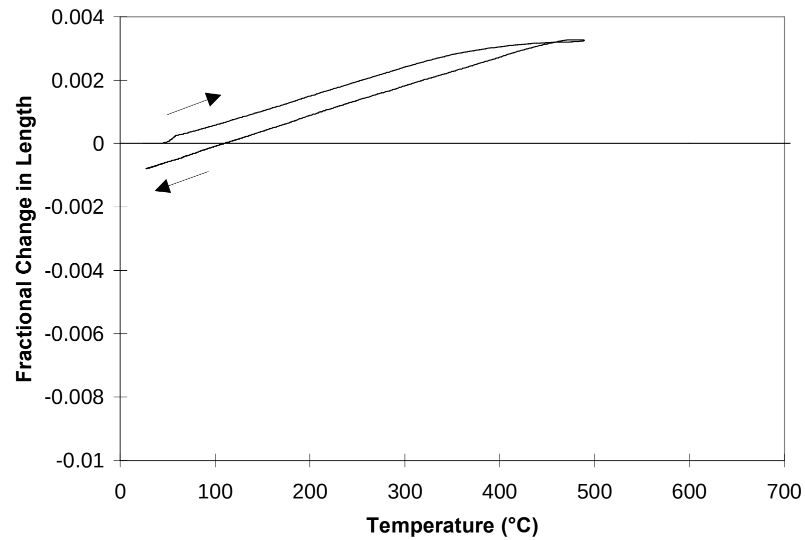
A suite of measurements suggests elasto-plastic behavior is playing a role in length change

No annealing ⇒ residual stress



(a)

Annealed during processing ⇒No residual stress



(b)

Figure 3. (a) Fractional change in length of an ITER conductor produced by IGC-AS. This 19 sub-element wire with 50 % Cu is the same conductor as seen in figure 1(b). (b) Fractional change in length of a bronze-processed conductor produced by Hitachi. Same as the conductor of figure 1(a).

Conclusion: dip at 210C is due to stress relief between Nb tension and Cu, not Cu-Sn intermetallic phase creation

Note: these measurements do not tell us about the radial growth vs T

Unconfined Cables

Figure 7: a) Measuring cable length, b) in the unconfined case, the cables are placed between siderails, top & bottom plates are tied together

Confined Cables

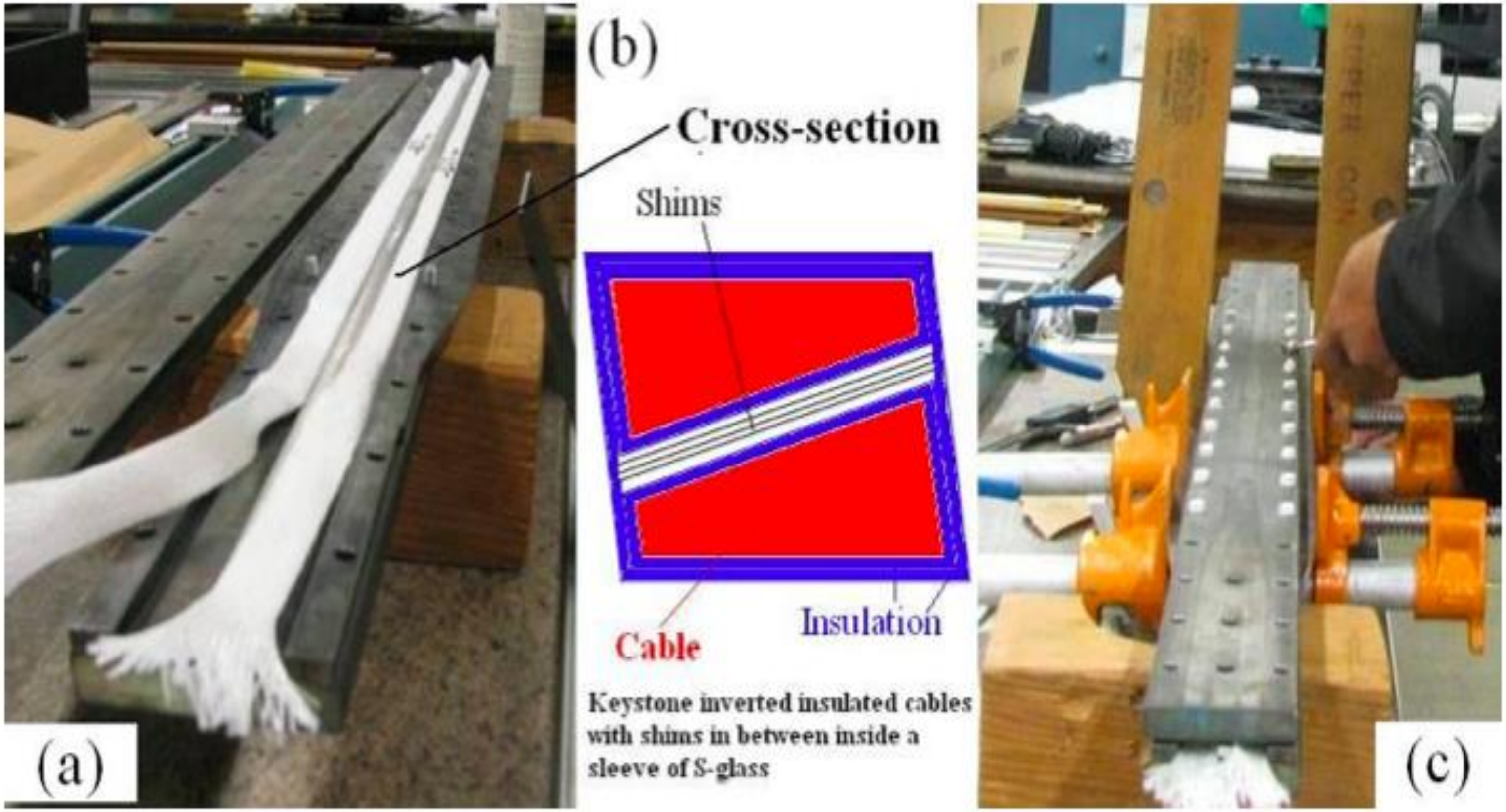
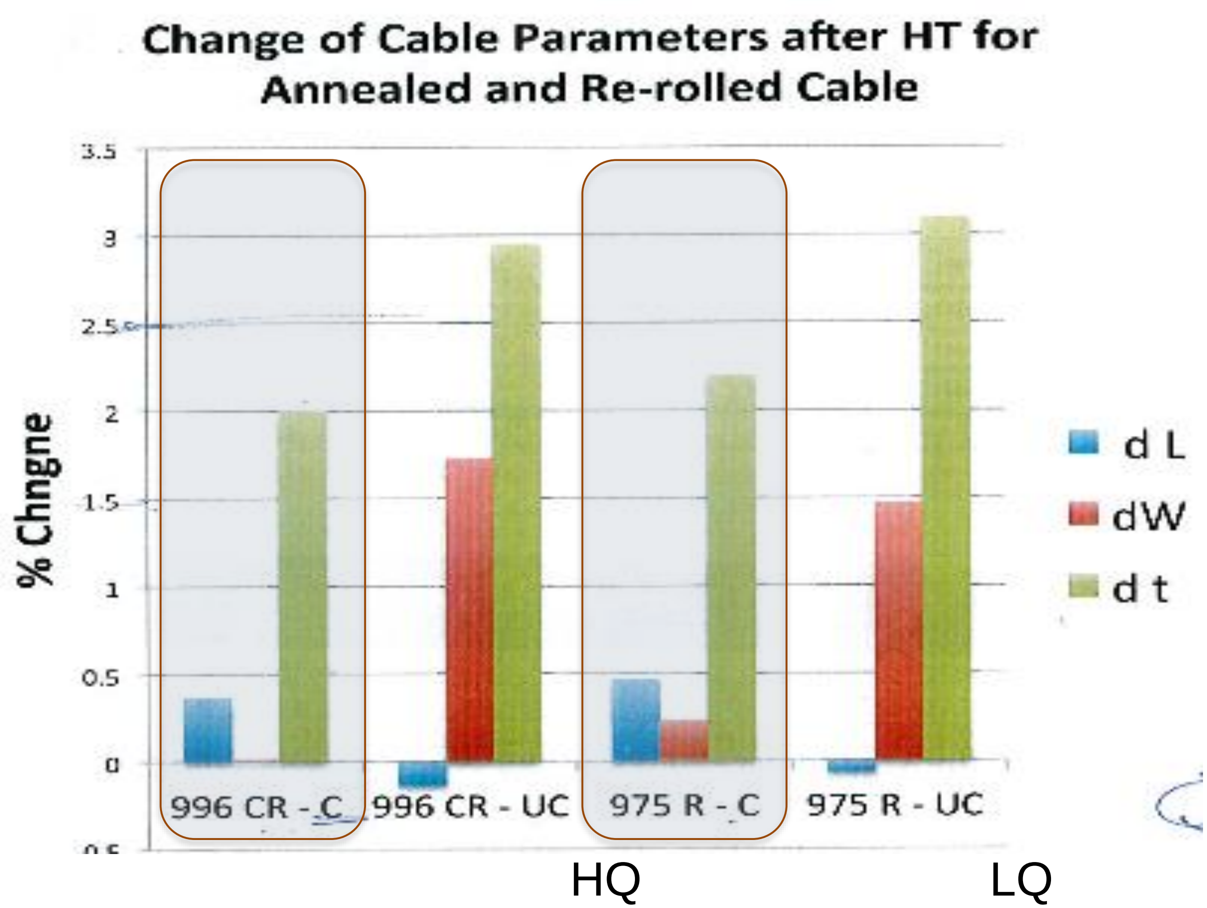


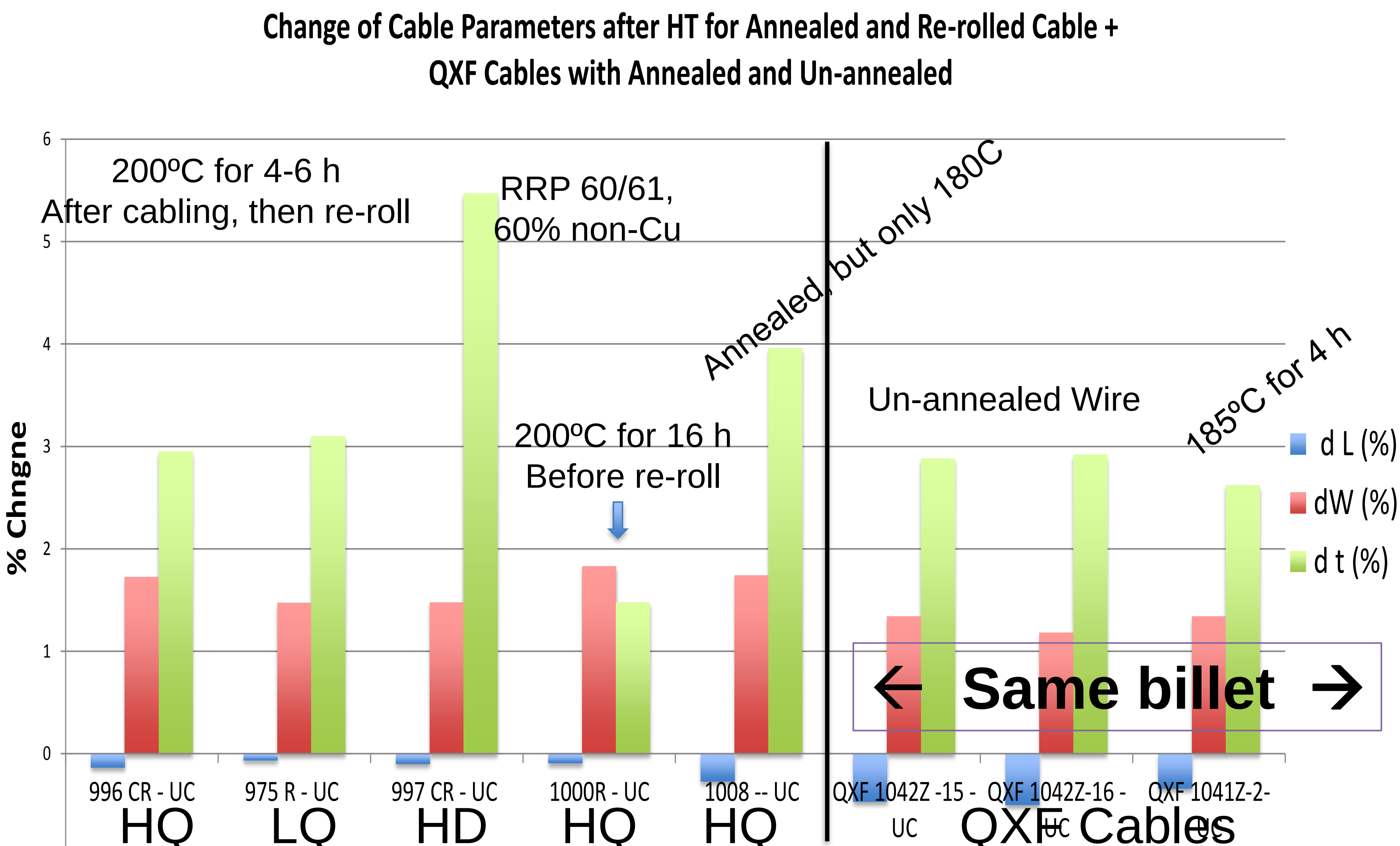
Figure 6: a) & b) The cables in the tooling, c) top plate is bolted on while the width is maintained by wooden blocks

Confining cables during reaction has a significant impact on dimensional change



Confining cables reduces width and thickness expansion; cable length increases

Exploration of unconfined cable dimensional changes highlights some correlations of interest, e.g. un-annealed vs annealed



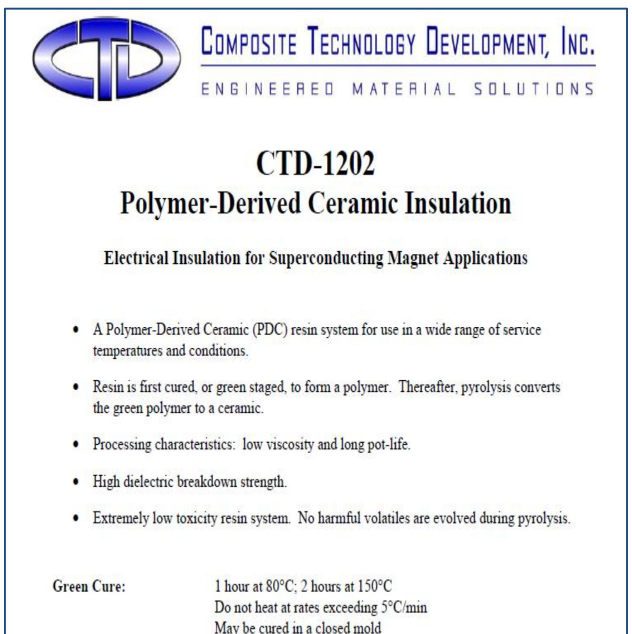
Detailed measurements were performed on QXF cables

- Cable Samples ("1st Generation")
  - SQXF03 Inner - P33OL1053CB(70)B*
  - SQXF-PC01b - P35OL1056AB(70)B
  - SQXF04 Inner - P33OL1057AA(00)B
  - SQXF05 Outer - P33OL1057AD(40)B
- Details
  - 108/127, Ti-doped, reduced-Sn, 0.55° KS; annealed prior to cabling
  - 132/169, Ti-doped, Standard-Sn, 0.55° KS; annealed prior to cabling
  - 108/127, Ti-doped, reduced-Sn, 0.55° KS; annealed prior to cabling
  - 108/127, Ti-doped, reduced-Sn, 0.55° KS; annealed prior to cabling

* This cable was test-wound on a Selva winder and subsequently straightened. It had matrix painted on the insulation every ~24" in 6 to 12" painted sections.

Reaction Method for unconfined cables

- S2-glass Sleeve
- S2-glass Braid
- S2-glass Braid + CTD-1202 Matrix


COMPOSITE TECHNOLOGY DEVELOPMENT, INC.

ENGINEERED MATERIAL SOLUTIONS

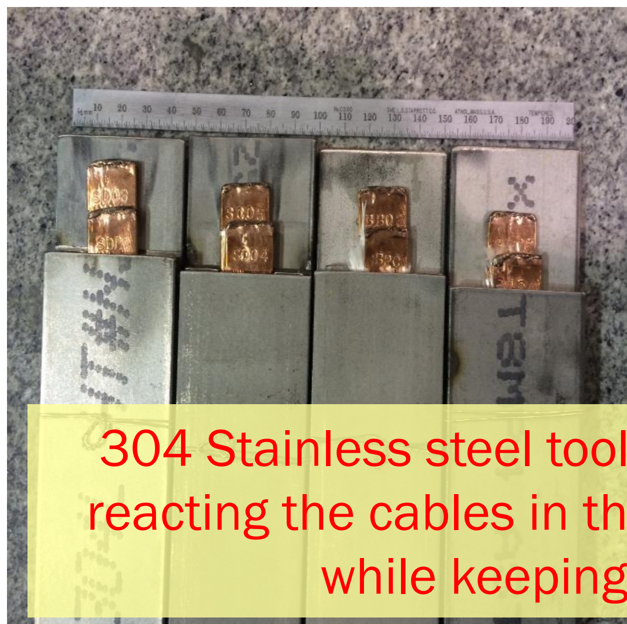
CTD-1202

Polymer-Derived Ceramic Insulation

Electrical Insulation for Superconducting Magnet Applications

- A Polymer-Derived Ceramic (PDC) resin system for use in a wide range of service temperatures and conditions.
- Resin is first cured, or green staged, to form a polymer. Thereafter, pyrolysis converts the green polymer to a ceramic.
- Processing characteristics: low viscosity and long pot-life.
- High dielectric breakdown strength.
- Extremely low toxicity resin system. No harmful volatiles are evolved during pyrolysis.

Green Cure: 1 hour at 80°C; 2 hours at 150°C
Do not heat at rates exceeding 5°C/min
May be cured in a closed mold



304 Stainless steel tooling held by wire wrap for reacting the cables in the "unconfined" condition while keeping them straight.

Heat Treatment

- 210°C for 72h + 405°C for 50h + 654°C for 50h and furnace cooled
- ± 5°C and ± 5 h at dwell; under flowing Ar

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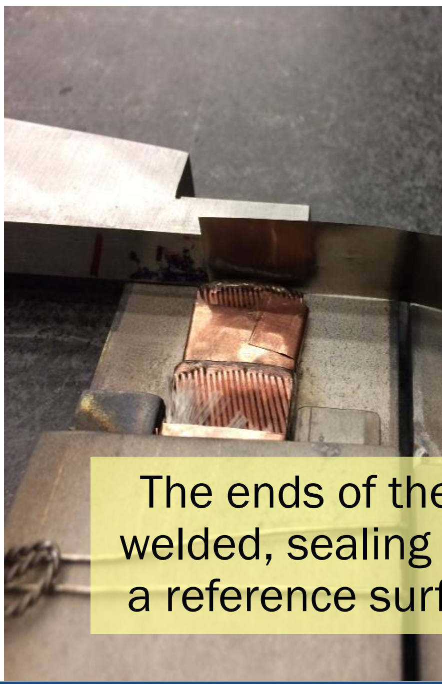
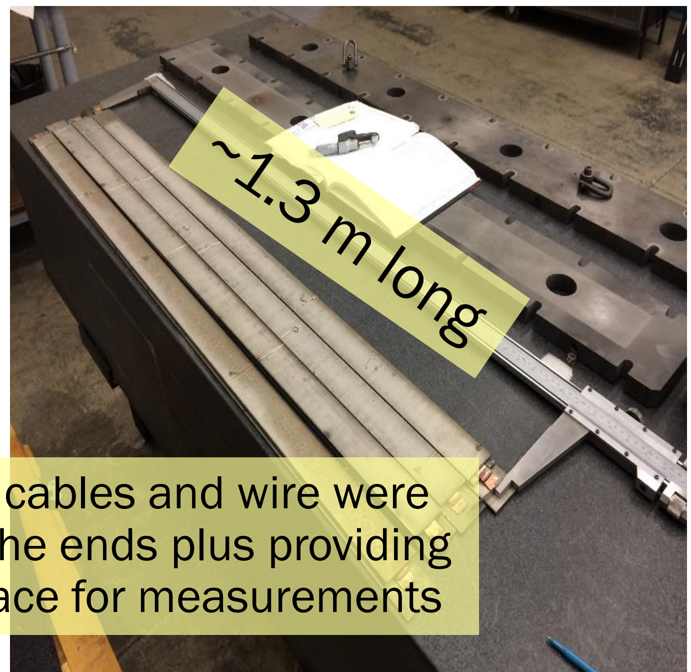
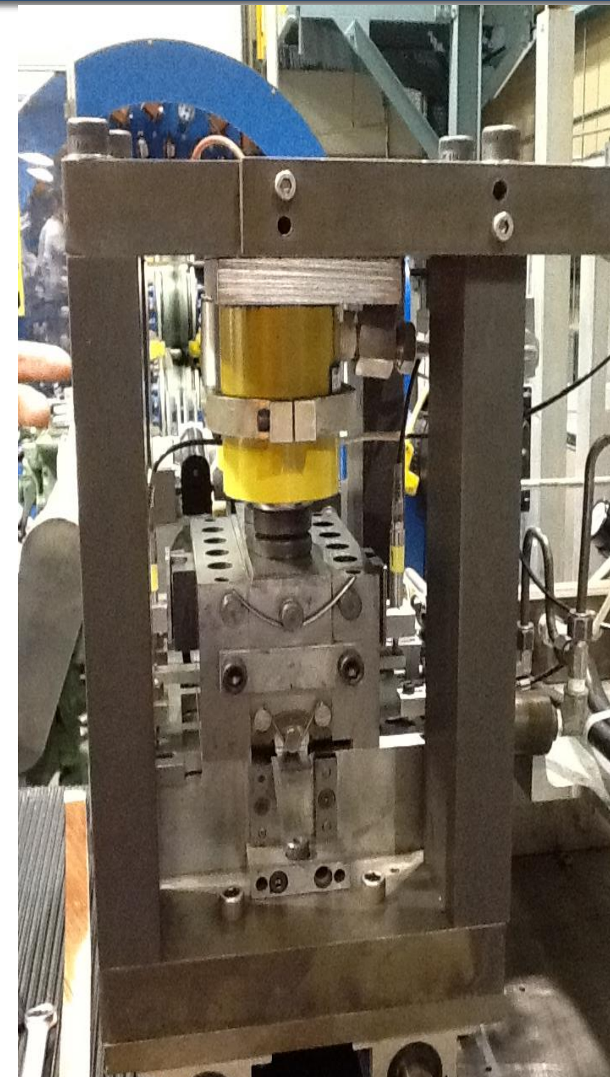
Measurement Methods

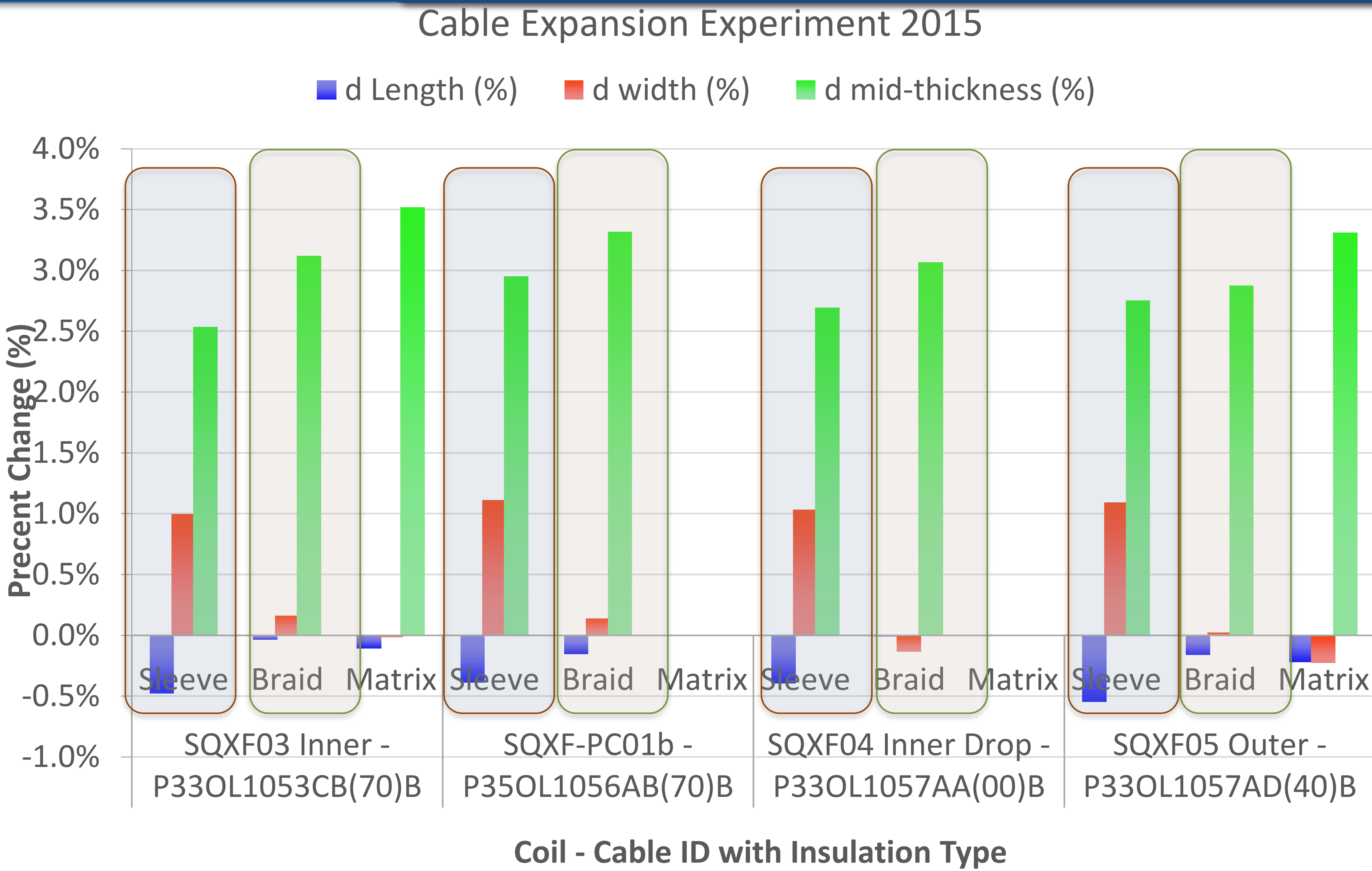
- Length measured with a caliper (±0.002”)
- Width measured with 500PSI (3.45MPa)
- Mid-thickness and keystone angle measured by CME (17 MPa)







Results



Cable Expansion Experiment 2015
d Length (%)
d width (%)
d mid-thickness (%)
4.0%
3.5%
3.0%
2.5%
2.0%
1.5%
1.0%
0.5%
0.0%
-0.5%
-1.0%
Precent Change (%)
Sleeve
Braid
Matrix
SQXF03 Inner - P33OL1053CB(70)B
SQXF-PC01b - P35OL1056AB(70)B
SQXF04 Inner Drop - P33OL1057AA(00)B
SQXF05 Outer - P33OL1057AD(40)B
Coil - Cable ID with Insulation Type

We can glean some tentative conclusions from these measurements

- Confined and unconfined cables behave differently
  - Width and thickness always increase; length shrinks when unconfined whereas cable elongates when confined
  - Volume is not fully conserved; void formation varies
- Braid and sleeve have different effect on cable dimension change during heat treatment → impact of insulation
  - braid is like a cable with width confined
- "Matrix material" degrades the braid but the effect on cable dimension change is similar: ~3% increase in mid-thickness

We have managed to overcome big issues, but full understanding of heat treatment implications remains a somewhat empirical process

Experience with HQ demonstrated that proper confinement dimensioning is critical

From H. Felice, "Status on HQ Coil Design and Fabrication", 17th LARP, 1st HiLumi collaboration meeting

Study on unconfined cables

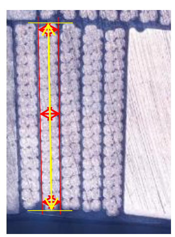
Meas. performed at LBNL by J. Krishnan

- axial contraction: 0.1 to 0.3 %
- thickness increase: 1.4 to 4 %
- width increase: 1.5 to 2 %

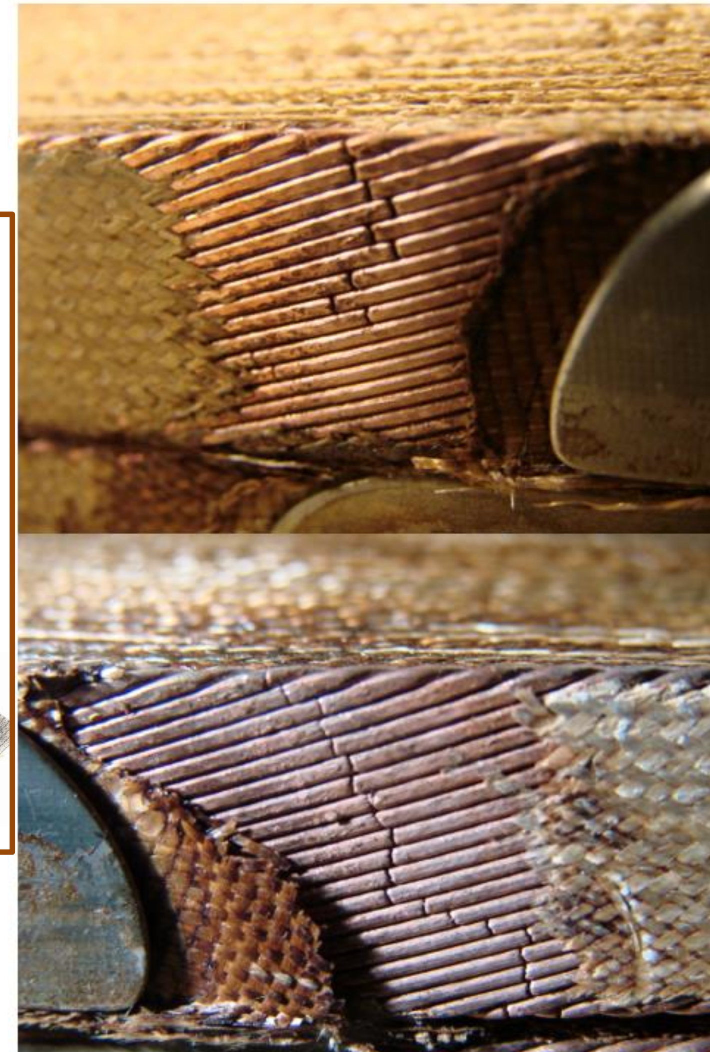
Study on sections of LQ - TQ and HQ coils

Thickness
LQ and TQ: 5.6 and 6% of increase
HQ: only 1 to 2 % of increase

Width
LQ and TQ => 1 to 2 % of increase
HQ => 1 % of increase



Meas. Performed at FNAL D. Bocian, M. Bossert



Solution in HQ case was to provide more "room" for cable expansion during reaction

In conclusion… There are many questions that we can ask ourselves…

1. Does the reaction phase impart real force on confining structures, or are the forces we see due to differential thermal expansion of structural materials?
    - Suggests detailed elasto-plastic calculations using temperature-dependent properties
2. What is the variability in volumetric change in conductors? In cables? Does it depend strongly on conductor architecture?
3. Is there a correlation between anneal, volumetric change, void creation, and sensitivity to strain degradation?