Crack Growth Response of Alloy 690 in Simulated PWR Primary Water

Mychailo Toloczko and Steve Bruemmer
Pacific Northwest National Laboratory

Research Supported by the
U.S. Nuclear Regulatory Commission

NRC Project Manager: Darrell Dunn

Presented at the 14th International Conference on
Environmental Degradation of Materials in Nuclear Power Systems

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

Pacific Northwest
NATIONAL LABORATORY

Alloy 690 Crack Growth Tests in Simulated PWR Water at PNNL

- *Research has focused on testing of specimens made from alloy 690 CRDM tubing obtained from Valinox Nucléaire.*

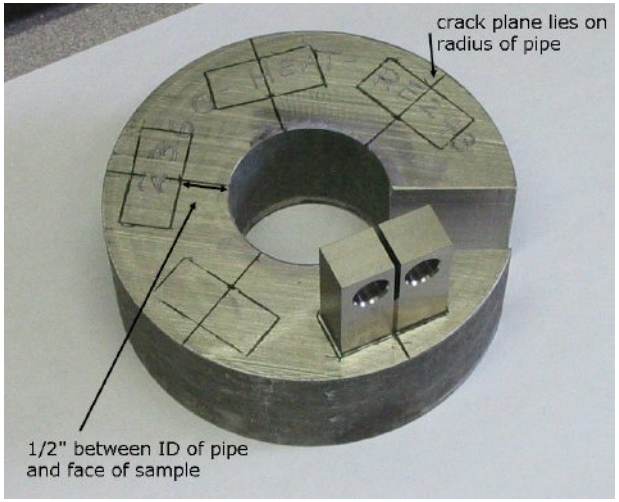
- **Alloy 690 CRDM Testing - eight specimens tested**
  - Valinox CRDM Heat RE243: specimen CT014 in a carbide-modified (CM) condition, specimen CT015 in the as-received thermally treated (TT) condition
  - Valinox CRDM Heat: specimen CT026 is heat WP142 in TT condition, specimen CT027 is heat WP140 in TT condition
  - Valinox CRDM Heat RE243, specimen CT020 in TT + 17% CR S-L condition, specimen CT019 in CM + 17% CR S-L condition
  - Valinox CRDM Heat RE243, specimen CT022 in a TT + 30% CR T-L condition, specimen CT023 in CM + 30% CR T-L condition

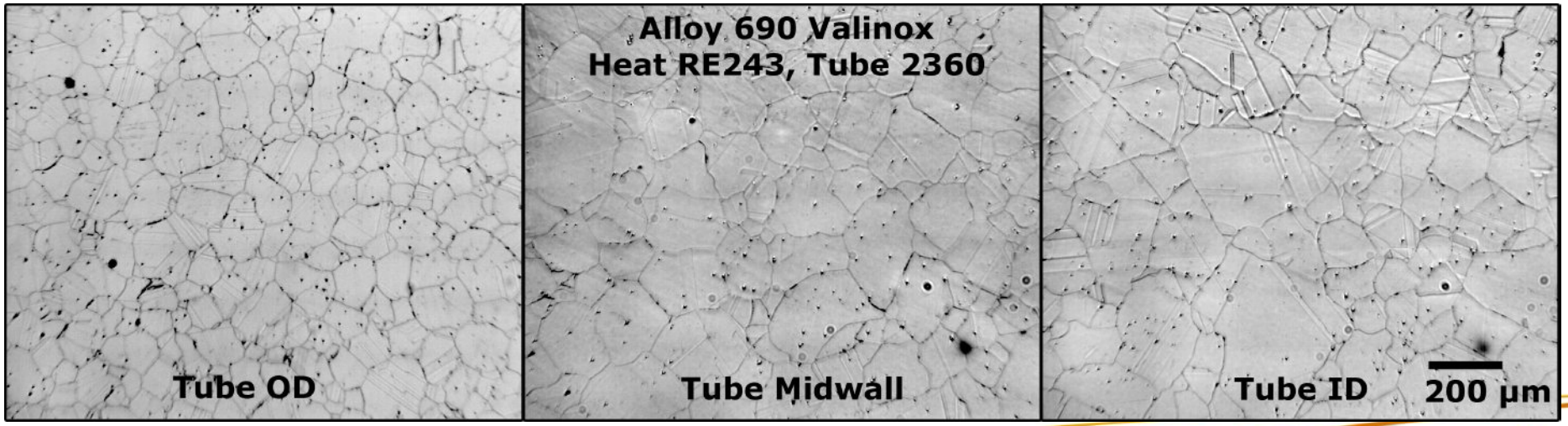
Alloy 690 CRDM Materials

- Alloy 690 CRDM tubing obtained from Valinox Nucléaire
  - Seven tubes
  - Several different tubing dimensions, but ~110 mm OD x ~55 mm ID
  - Six different heats (two tubes made from the same heat)
- Compositions
  - RE243: 10.4Fe, 28.9Cr, 0.02C, 0.31Mn, 0.35Si, 0.14Al, 0.23Ti, Bal Ni
  - WP142: 10.5Fe, 29.0Cr, 0.02C, 0.31Mn, 0.35Si, 0.18Al, 0.27Ti, Bal Ni
  - WP140: 10.4Fe, 29.0Cr, 0.03C, 0.31Mn, 0.33Si, 0.18Al, 0.30Ti, Bal Ni

Alloy 690 General Microstructure

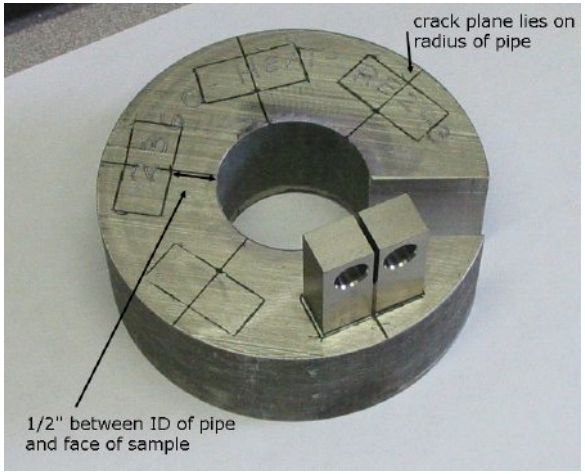
- Equiaxed grain dimensions
- Grain size near tube OD about ½ the size compare to midwall and ID
- Specimens cut from mid-thickness or near tube ID





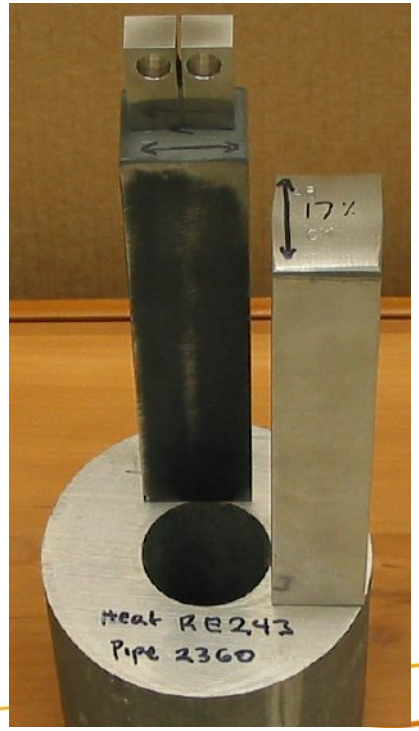
Alloy 690 Thermomechanical Treatments and CT Specimen Orientation

- Thermomechanical conditions
  - As-received thermally treated (TT) condition
  - Carbide modified (CM): AR+1100°C/1h/WQ
  - 17% CR S-L: achieved in two passes
  - 30% CR T-L: achieved in six passes
- All specimens cut from a C-L orientation



RE243 non-CR

RE243 30% CR T-L



RE243 17% CR S-L

WP140, WP142

Crack Growth Testing Methodology

- Alloy 690/152/52 has been resistant to stress corrosion cracking in nearly all material conditions, and has been difficult to obtain stable crack growth at constant K.
- As a means to assess constant K growth rates and obtain maximum SCC crack front engagement, different transitioning methods have been investigated and are routinely used.
  - Varied R from 0.5 to 0.7
  - Varied hold time
  - Varied length of time at each step during transitioning
  - Varied cyclic loading waveform rise time and fall time
- Transition to constant K several times in each test.
- As possible, examine crack growth response at two K levels.

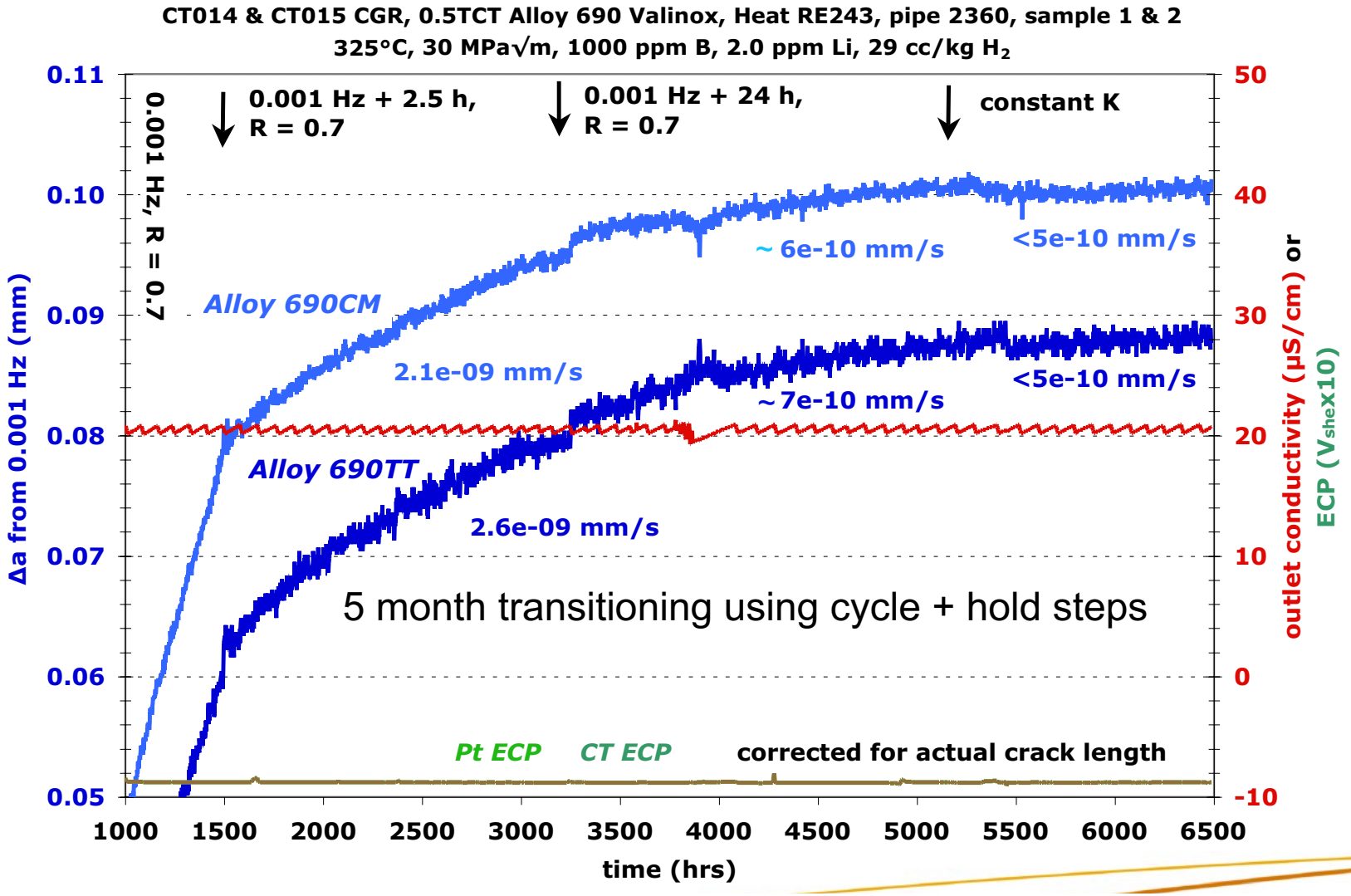
Crack Growth Rate Measurement

- Several ways to calculate crack growth rate using final DCPD data corrected from observed post-test fracture surface. Can be a key issue for alloy 690/152/52 since SCC engagement is often limited to “fingers” of growth.
- ***Average crack growth rate:*** *Crack-growth rate based on average final crack length determined across the full crack front.*
- Average crack growth rate of engaged regions: Average of crack growth rate from SCC regions only, can be done if **IG** cracking is present.
- Maximum SCC growth rate: Crack growth rate based on the maximum extent (e.g., IG) of the crack growth surface.

Alloy 690 Crack Growth Tests in Simulated PWR Water at PNNL

- **Alloy 690 CRDM Testing - eight specimens tested**
  - ***Valinox CRDM Heat RE243: specimen CT014 in a carbide-modified (CM) condition, specimen CT015 in the as-received thermally treated (TT) condition***
  - ***Valinox CRDM Heat: specimen CT026 is heat WP142 in as-received TT condition, specimen CT027 is heat WP140 in TT condition***
  - Valinox CRDM Heat RE243, specimen CT019 in CM + 17% CR S-L condition, specimen CT020 in TT + 17% CR S-L condition
  - Valinox CRDM Heat RE243, specimen CT022 in a TT + 30% CR T-L condition, specimen CT023 in CM + 30% CR T-L condition

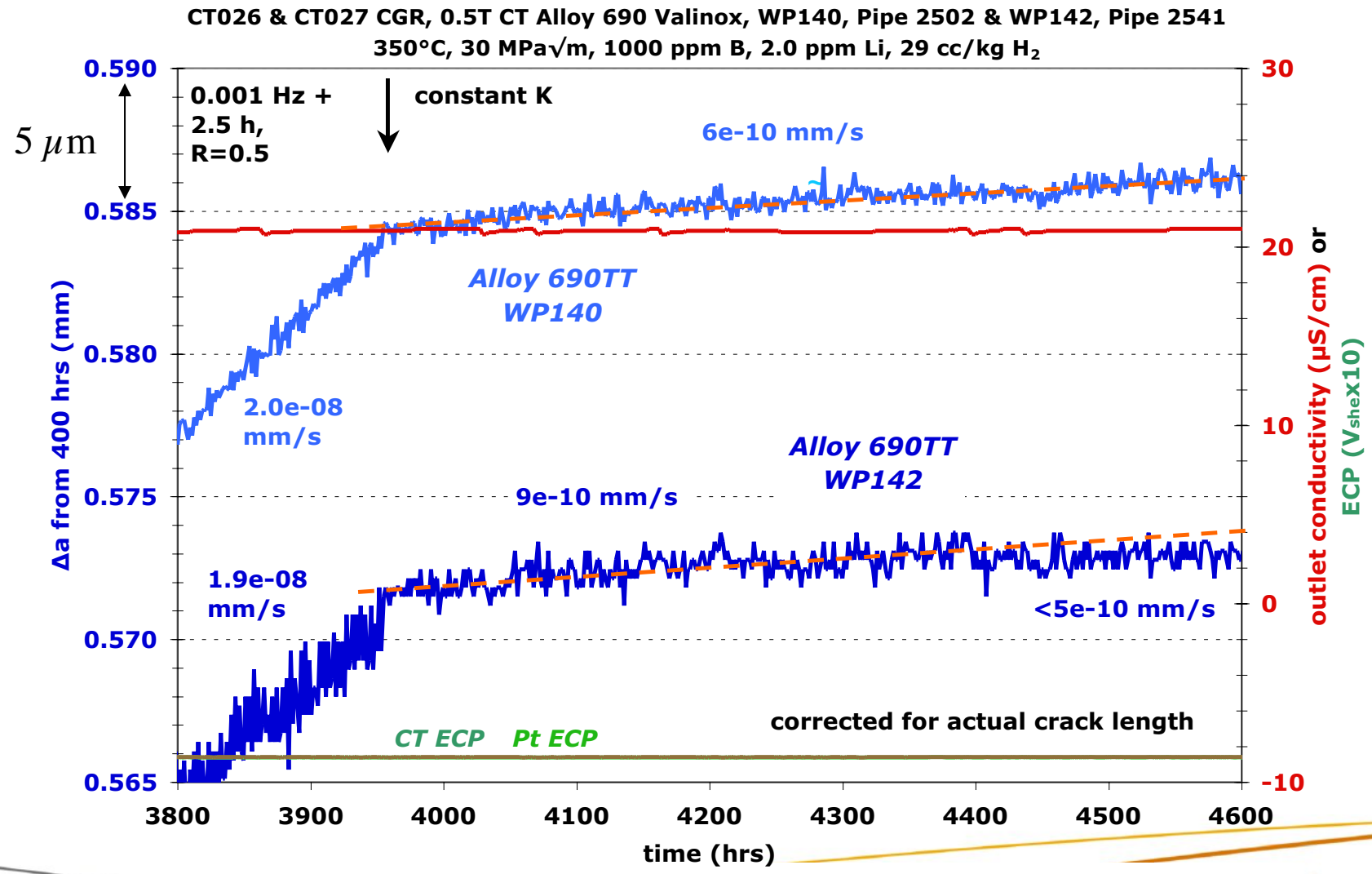
Alloy 690 TT/CM, Heat RE243 Crack Transitioning and Constant K



Transitioning and constant K response, reproduced at higher K levels

Pacific Northwest
NATIONAL LABORATORY

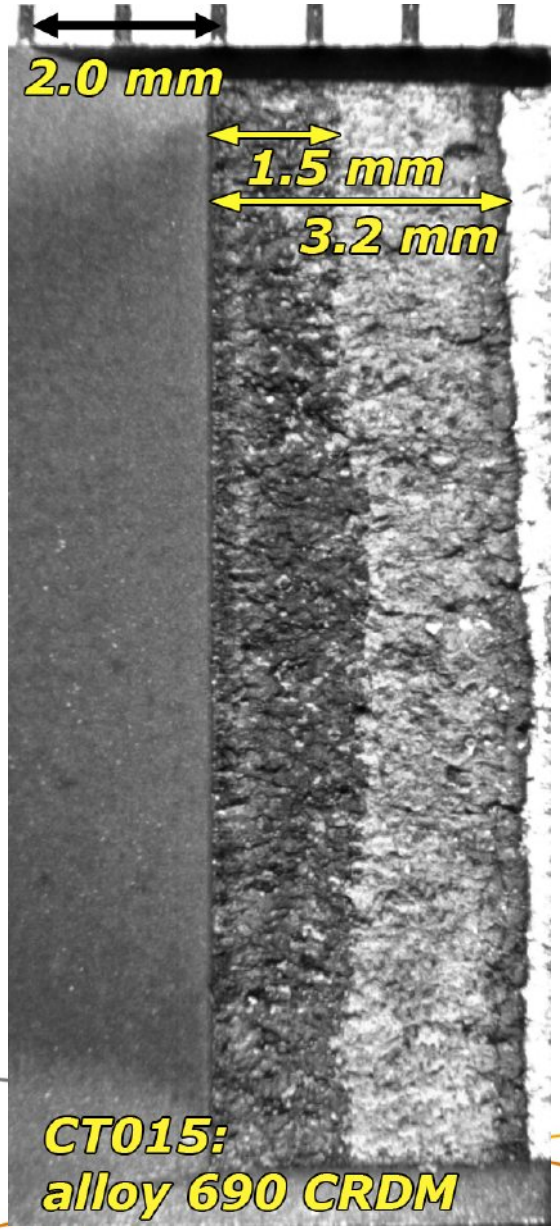
Alloy 690 TT, Heats WP140 & WP142 Constant K



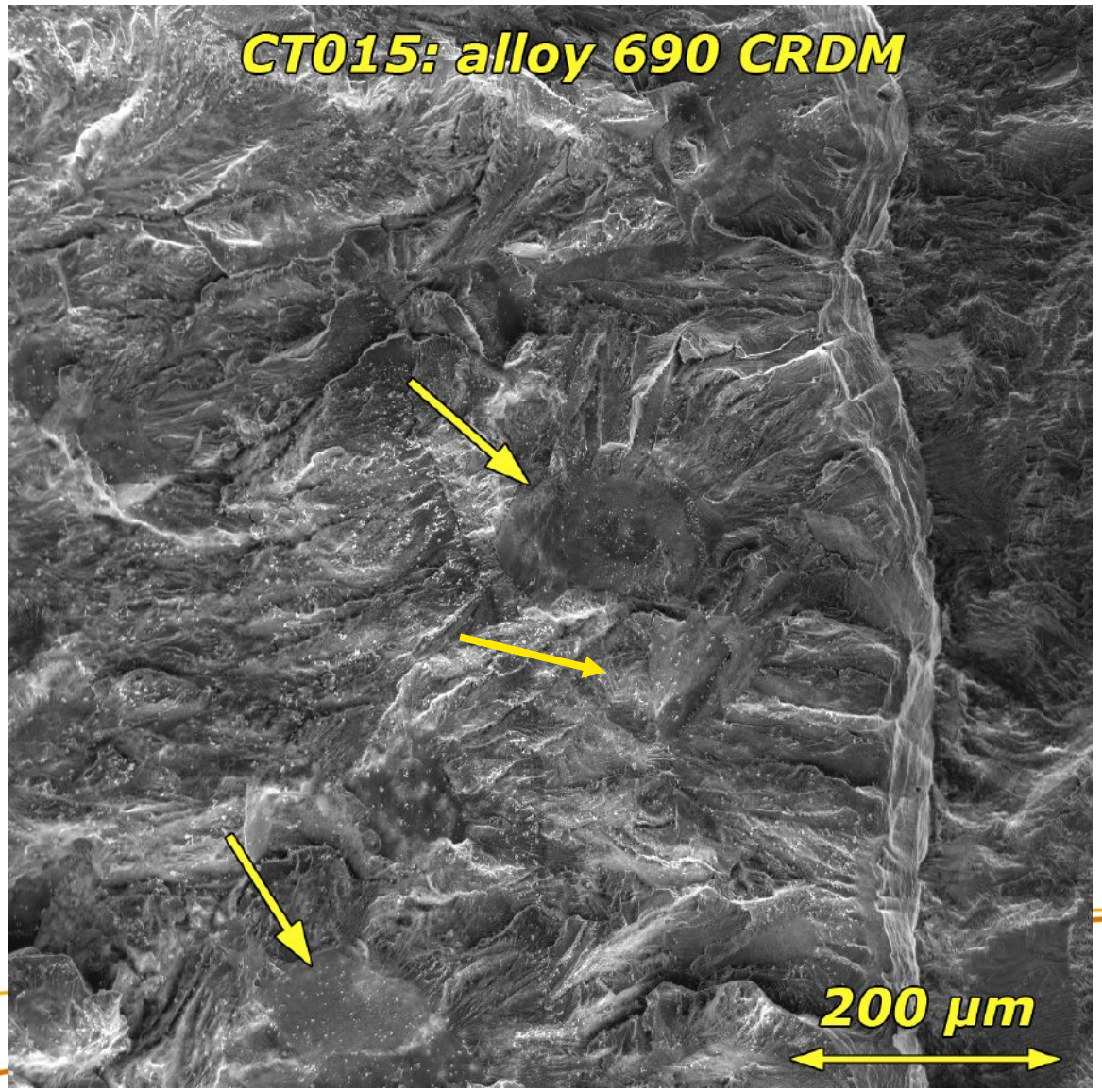
Crack growth rates are similar to those obtained in Heat RE243

Pacific Northwest NATIONAL LABORATORY

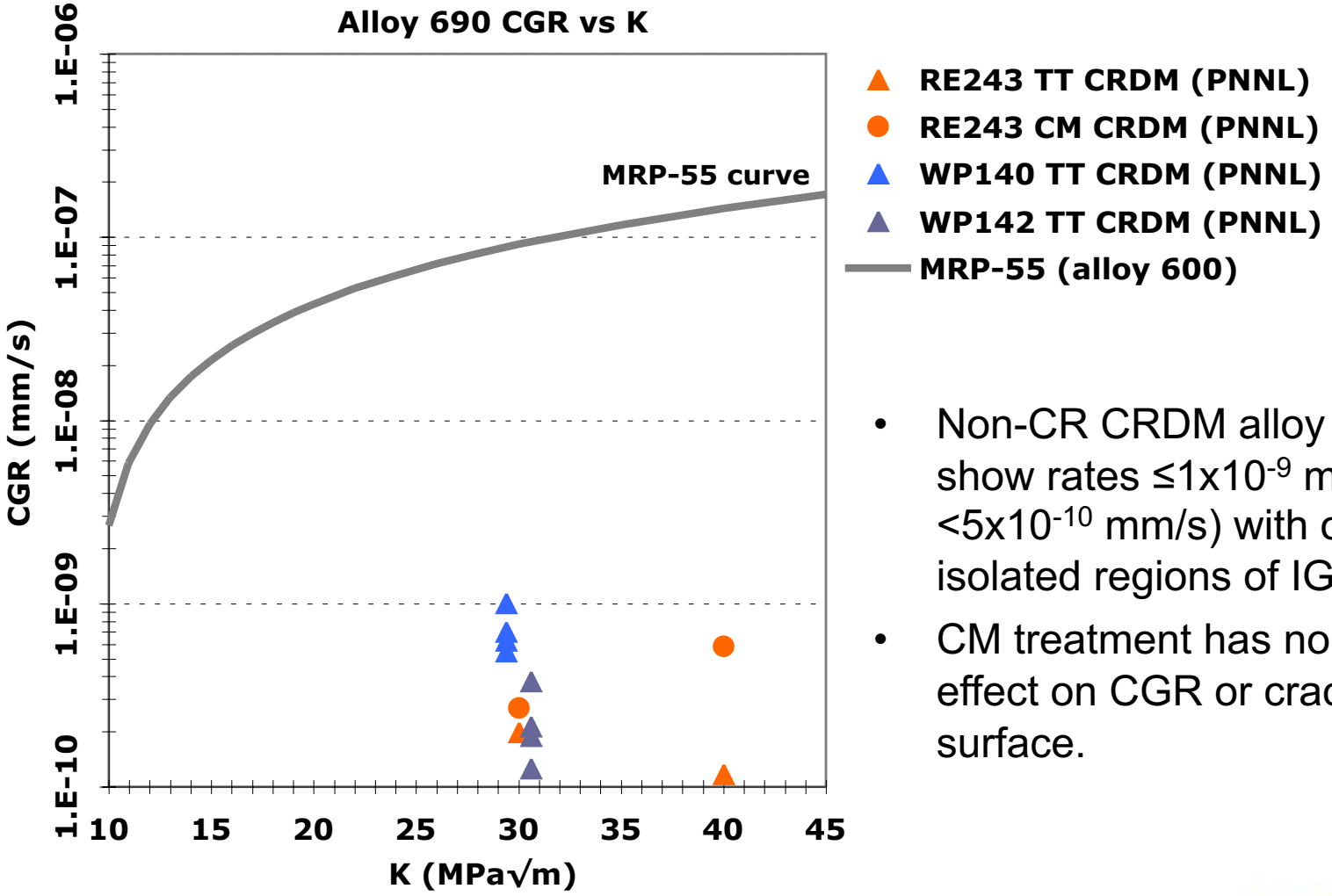
Alloy 690 Heat RE243 (TT/CM)
Crack Growth Surface



IG cracking limited to isolated grains



Very Low SCC Crack-Growth Rates Measured for *CRDM* Alloy 690 Heats

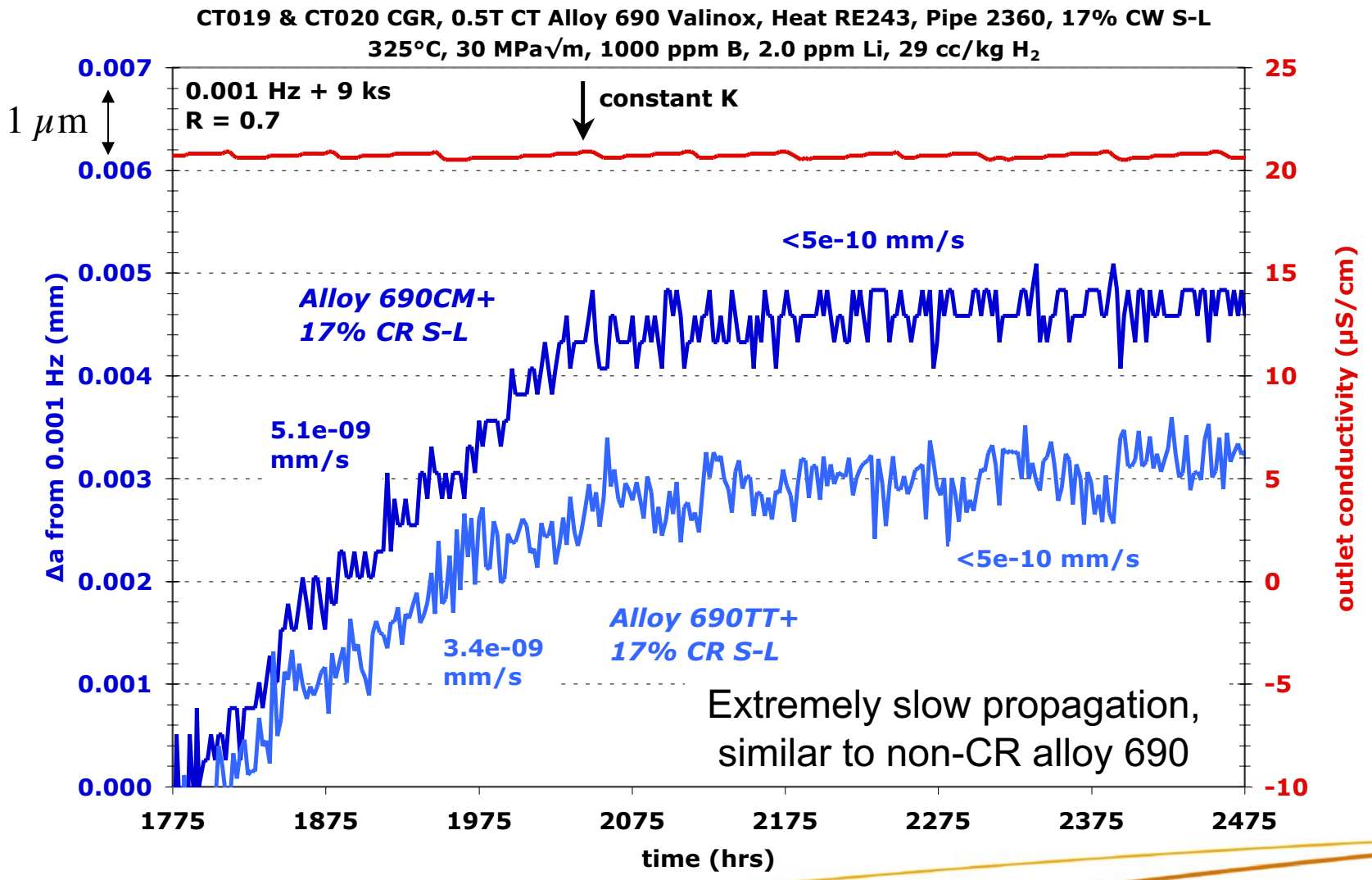


- Non-CR CRDM alloy 690 heats show rates ≤$1x10^{-9}$ mm/s (most <$5x10^{-10}$ mm/s) with only isolated regions of IGSCC.
- CM treatment has no apparent effect on CGR or crack growth surface.

Alloy 690 Crack Growth Tests in Simulated PWR Water at PNNL

- **Alloy 690 CRDM Testing - eight specimens complete**
  - Valinox CRDM Heat RE243: specimen CT014 in a carbide-modified (CM) condition, specimen CT015 in the as-received thermally treated (TT) condition
  - Valinox CRDM Heat: specimen CT026 is heat WP142 in as-received TT condition, specimen CT027 is heat WP140 in TT condition
  - ***Valinox CRDM Heat RE243, specimen CT019 in CM + 17% CR S-L condition, specimen CT020 in TT + 17% CR S-L condition***
  - Valinox CRDM Heat RE243, specimen CT022 in a TT + 30% CR T-L condition, specimen CT023 in CM + 30% CR T-L condition

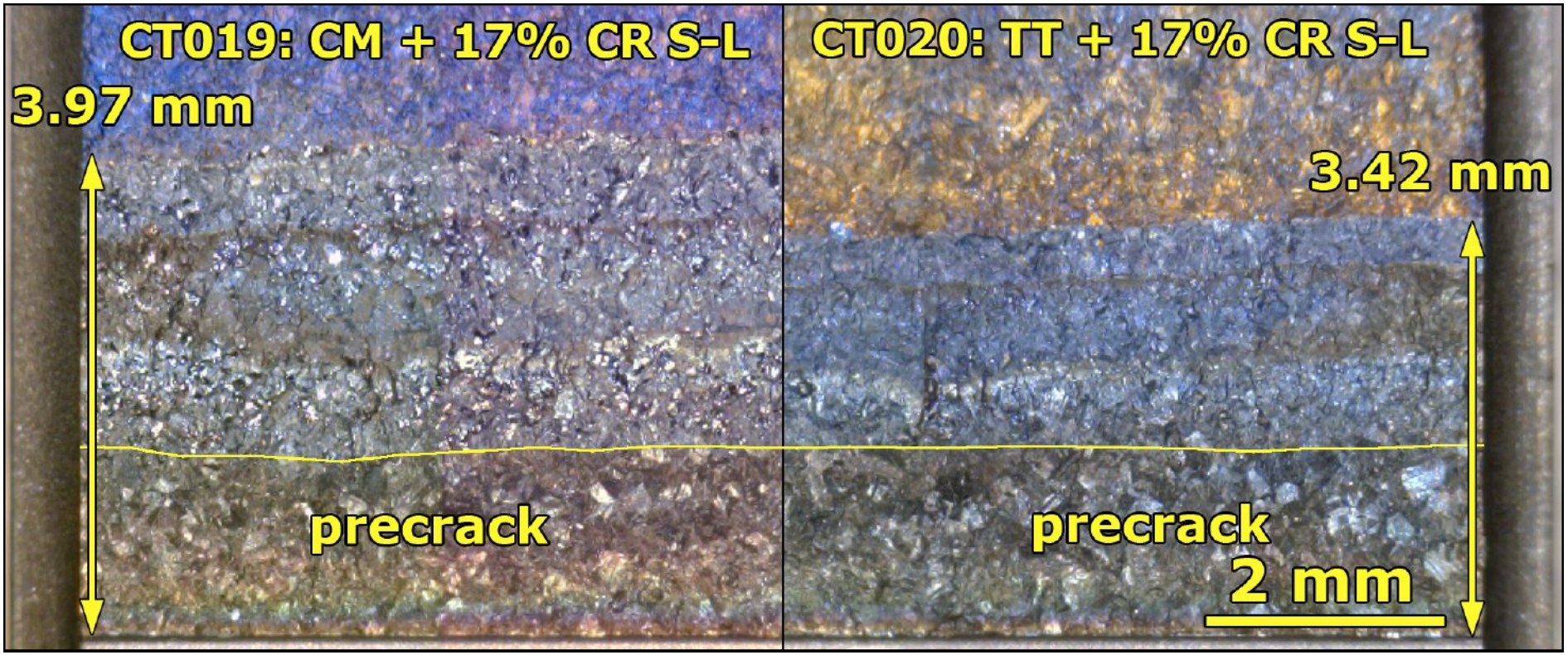
Alloy 690 Heat RE243 17% CW S-L Constant K



Example of constant K response, reproduced at higher K levels

Northwest
NAL LABORATORY

Alloy 690 Heat RE243 17% CR T-L Crack Growth Surface

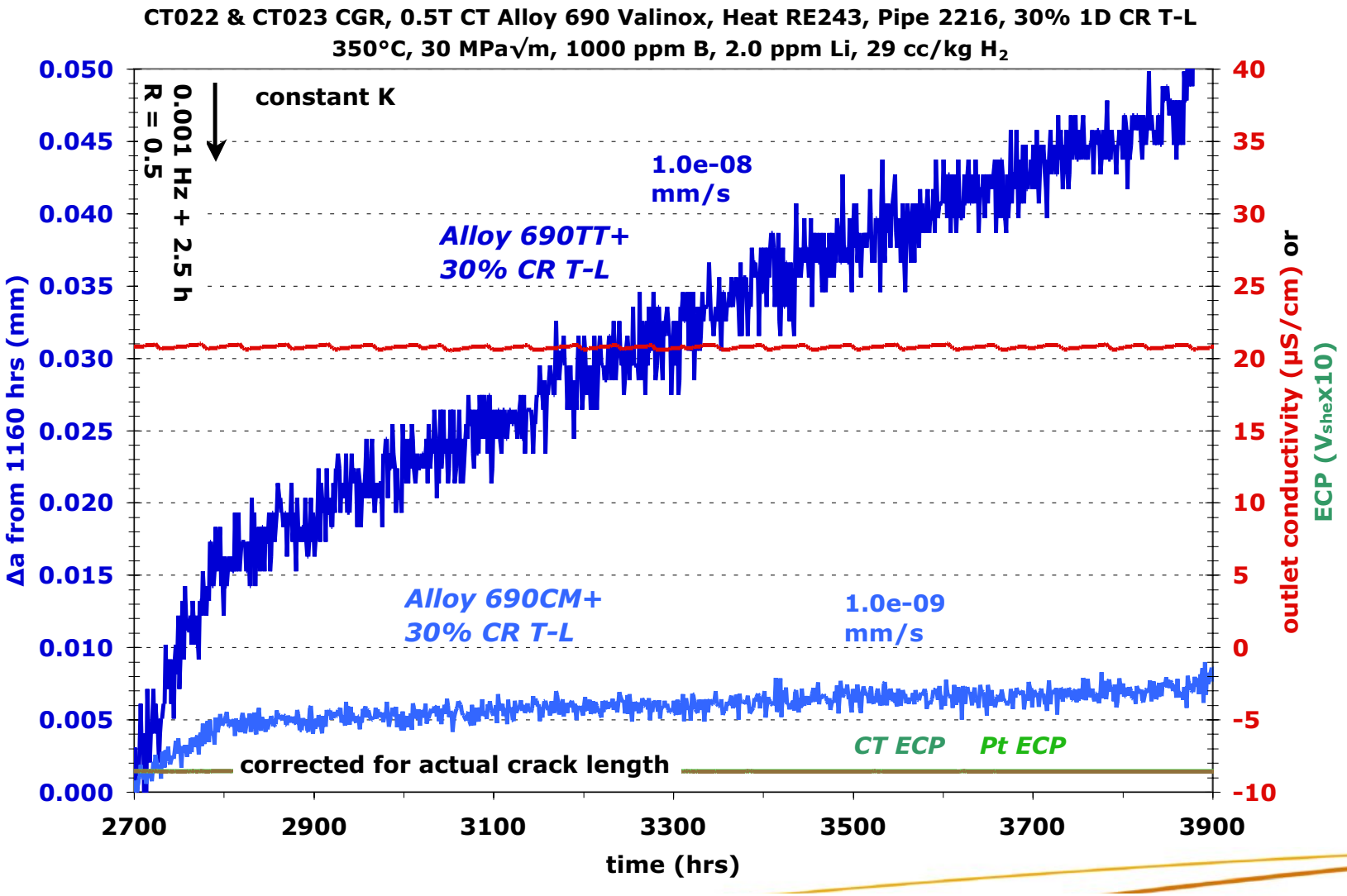


- Three distinct regions corresponding to three regions that were tested.
- CM+17%CR S-L material has higher fatigue CGRs than TT+17%CR S-L material.
- Approximately 15% IG cracking in CM material during gentle cycling and constant K, but constant K CGRs below $1x10^{-9}$ mm/s.

Alloy 690 Crack Growth Tests in Simulated PWR Water at PNNL

- **Alloy 690 CRDM Testing - eight specimens complete**
  - Valinox CRDM Heat RE243: specimen CT014 in a carbide-modified (CM) condition, specimen CT015 in the as-received thermally treated (TT) condition
  - Valinox CRDM Heat: specimen CT026 is heat WP142 in as-received TT condition, specimen CT027 is heat WP140 in TT condition
  - Valinox CRDM Heat RE243, specimen CT019 in CM + 17% CR S-L condition, specimen CT020 in TT + 17% CR S-L condition
  - ***Valinox CRDM Heat RE243, specimen CT022 in a TT + 30% CR T-L condition, specimen CT023 in CM + 30% CR T-L condition***

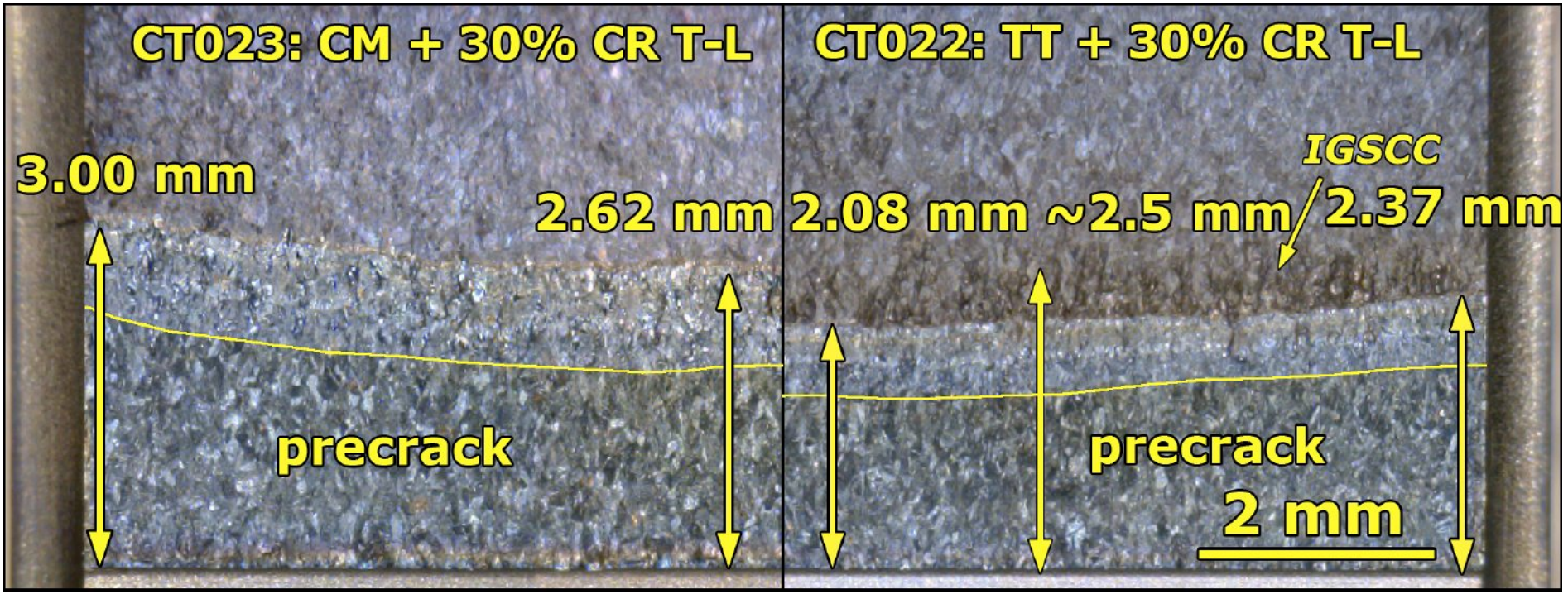
Alloy 690 Heat RE243 30% CW T-L Constant K



10x higher CGR in TT material, reproduced at higher K levels

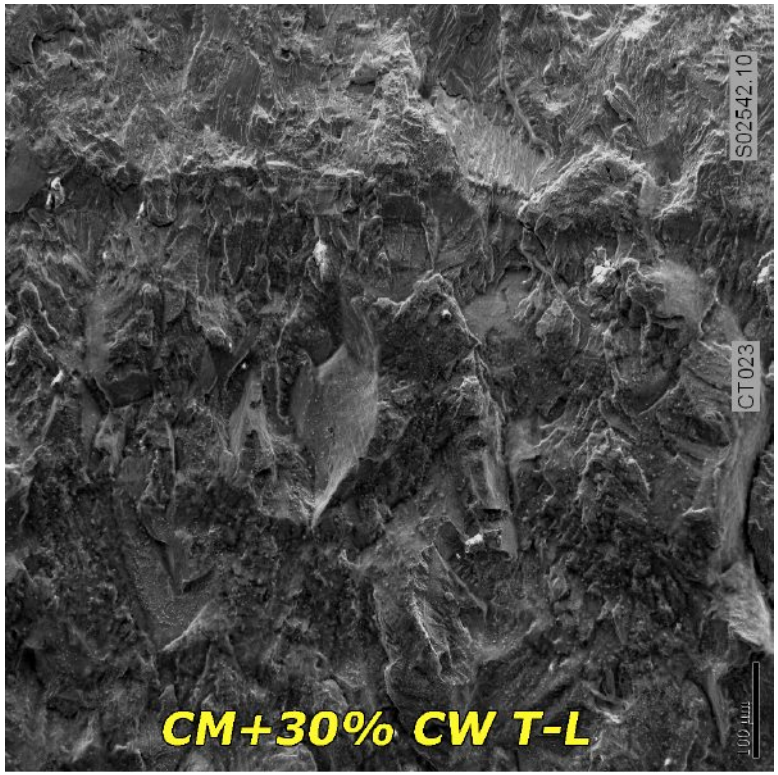
Pacific Northwest
NATIONAL LABORATORY

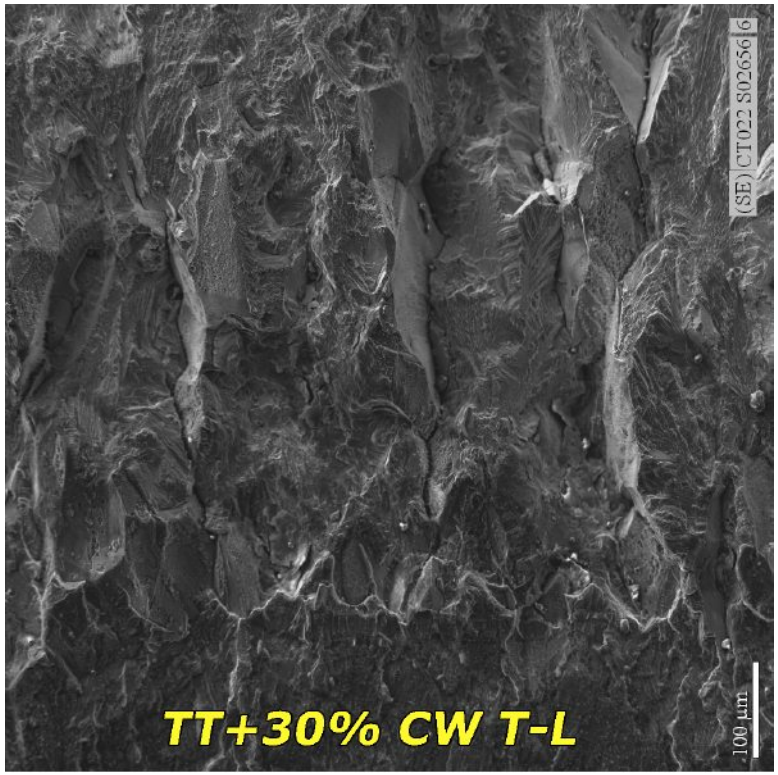
Alloy 690 Heat RE243 30% CR T-L Crack Growth Surface



- Alloy 690CM material has higher fatigue CGRs than TT, but only isolated IGSCC during gentle cycling and constant K (consistent with CM + 17% CR S-L).
- Alloy 690TT material transitions to a high degree of IGSCC (fingers) across the crack front during gentle cycling and constant K .

Alloy 690 Heat RE243 30% CR T-L Crack Growth Surface



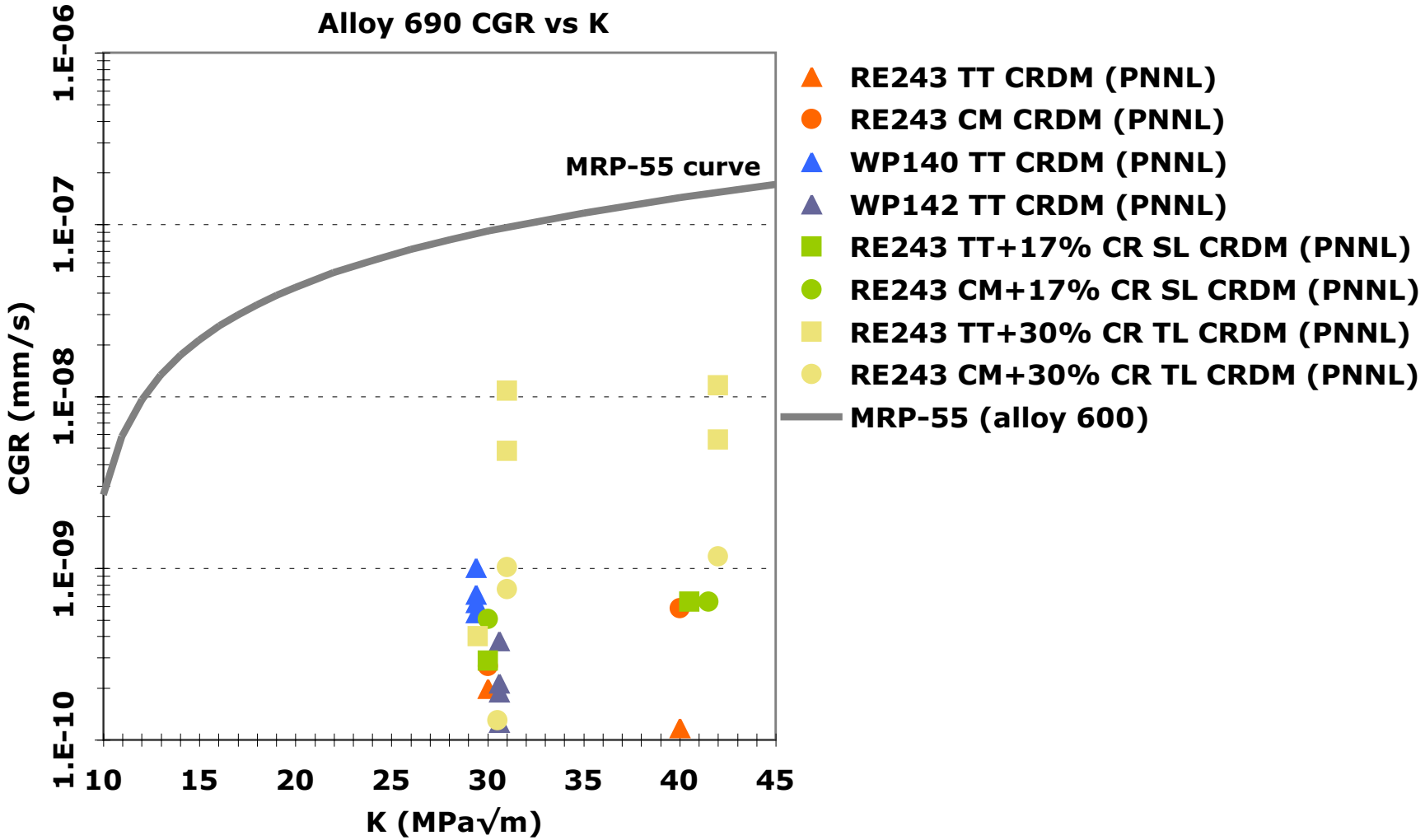


IG cracking limited to isolated grains similar to non-CR TT and CM material.

Higher fraction of IG cracking consistent with observed higher crack growth rates.

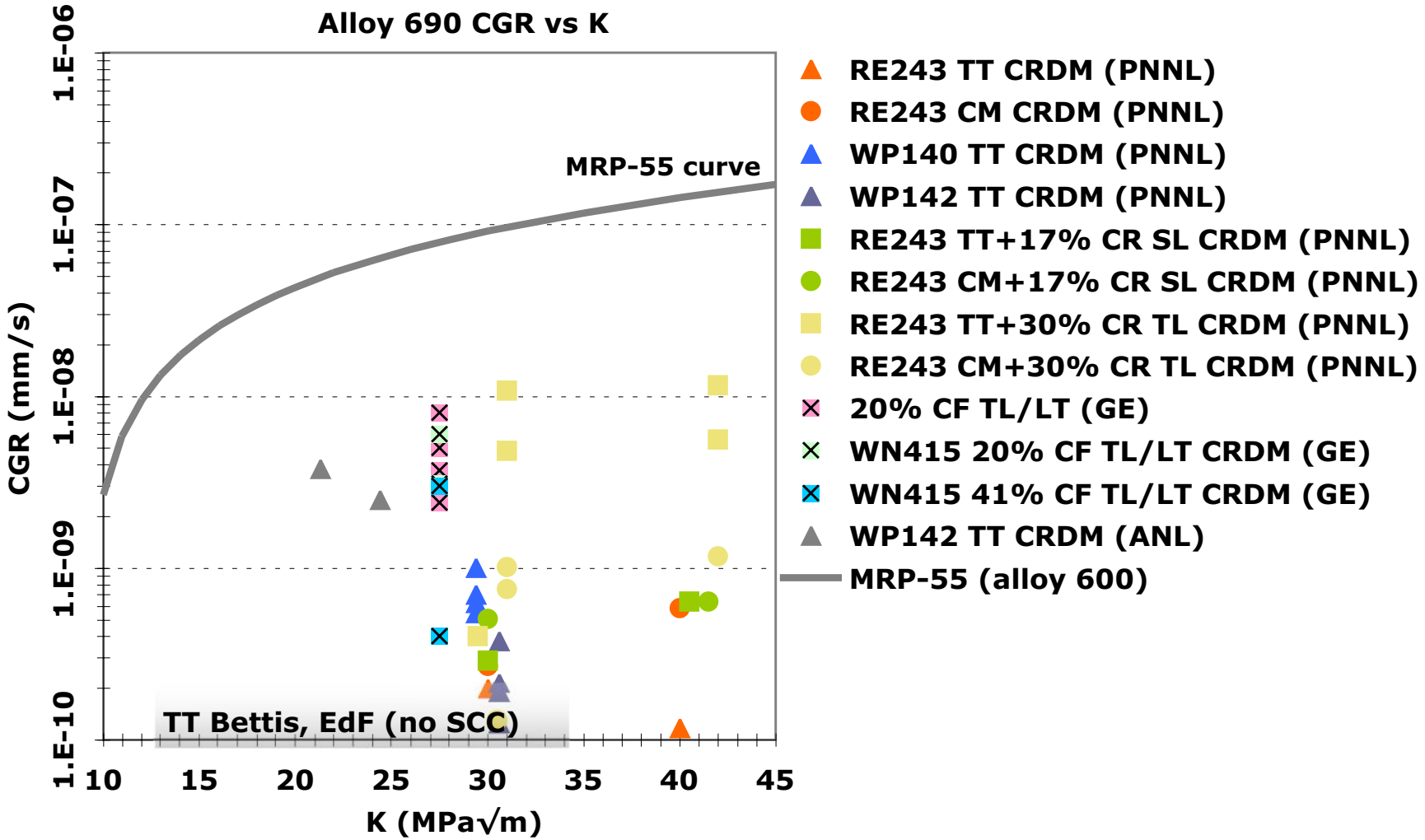
Most IG cracks are on grain boundaries that are parallel to the rolling plane.

Very Low SCC Crack-Growth Rates Measured for *CRDM* Alloy 690 Heats



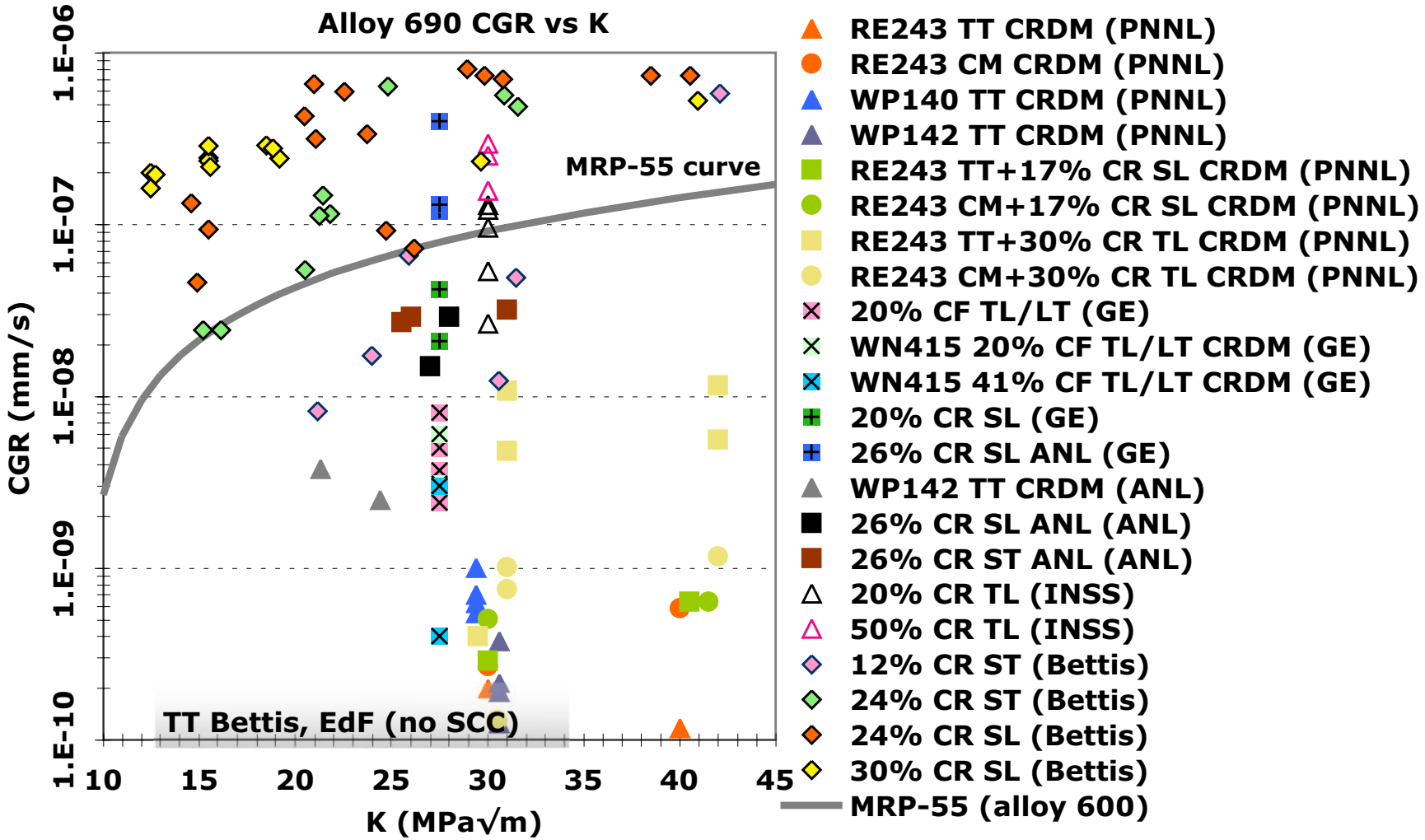
- Crack growth rates of all but the TT + 30% CR T-L are ≤1x10^{-9} mm/s.
- Similar response at 30 and 40 MPa√m.

Very Low SCC Crack-Growth Rates Measured for *CRDM* Alloy 690 Heats



- Higher crack growth rates in 30% CR T-L CRDM material are consistent with forged L-T alloy 690 CRDM and plate tested at GE-GRC.
- Non-CR CRDM alloy 690 heats shows rates <4×10^{-9} mm/s.

Wide Range of SCC CGR Response for Cold-Worked Alloy 690 Heats



- Extremely high crack growth rates in 1D CR alloy 690 plates (S-L and S-T)
- Preparation of higher CR S-L extruded CRDM materials underway to compare with results on higher CR S-L on plate material.

Alloy 690 Summary

- Both as-received TT and carbide-modified *CRDM* materials were evaluated in non cold-rolled and cold-rolled conditions.
- Extremely slow but generally stable propagation rates in alloy 690 CRDM materials (three different heats).
  - Non cold-rolled materials have constant K CGRs of ≤1x10^{-9} mm/s with only isolated IG facets.
  - Carbide modification treatment alone does not increase CGR or affect crack growth surface.
  - 17% CR S-L has increased IG cracking (≤ 15% IG) but same crack growth rate as non cold-rolled material.
  - CM + 30% CR T-L has similar response as 17% CR S-L materials.
  - TT + 30% CR T-L has extensive IG cracking and higher crack-growth rates consistent with forged T-L/L-T alloy 690 CRDM and plate.
  - CM + cold-rolled material appears to have a different PWSCC crack growth response than the TT + cold-rolled material.
- Preparations under way to test CRDM at higher CR S-L levels.