

Update on PNNL SCC Crack Growth Testing on Alloy 152, 52, 52M and 52MSS Welds

***Mychailo Toloczko, Matt Olszta,
and Steve Bruemmer***

Pacific Northwest National Laboratory

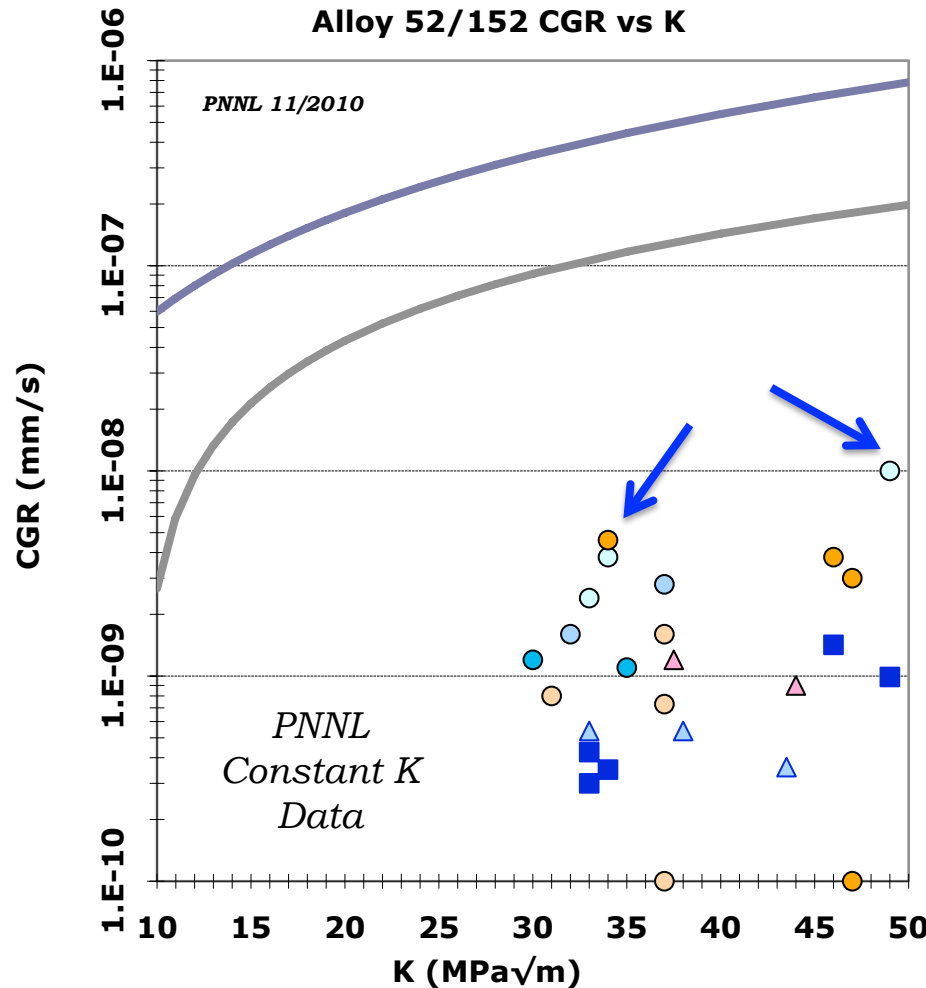
Research Supported by
U.S. Nuclear Regulator Commission
NRC Project Manager
Darrell Dunn

NRC – Industry 2011 Meeting on Alloy 690 Research
June 6-7, 2011 Rockville, MD

PNNL Weld Metal SCC Crack-Growth Testing Summary

- ▶ *Alloy 52 Mockup Welds*
 - *2 tests on an MHI U-groove weld*
 - *2 test on an AREVA butt weld*
- ▶ *Alloy 52M Inlay & Overlay Mockup Welds*
 - *3 tests on Ringhals overlay, **new post test analysis***
 - *2 tests on Ringhals inlay*
- ▶ *Alloy 52M Mockup Welds*
 - *1 test on KAPL V-groove weld, **new post test analysis***
 - *1 test on KAPL narrow gap weld*
 - *2 tests on KAPL NG weld with hot cracks*
- ▶ *Alloy 52MSS Mockup Weld*
 - ***Ongoing test on Special Metals weld***
- ▶ *Alloy 152 Mockup Welds*
 - *3 tests on an MHI U-groove weld (one with LAS SR)*
 - ***Ongoing tests on ANL V2 weld and 20%CF MHI weld***

Summary of Alloy 152/52/52M SCC Growth Rates at PNNL



- alloy 152 MHI (PNNL)
- △ alloy 52 MHI (PNNL)
- △ alloy 52 AREVA (PNNL)
- alloy 52M Ringhals Inlay (PNNL)
- alloy 52M Ringhals Overlay (PNNL)
- alloy 52M VG KAPL (PNNL)
- alloy 52M NG KAPL (PNNL)
- alloy 52M NG HC aligned KAPL (PNNL)
- alloy 52M NG HC non-aligned KAPL (PNNL)
- MRP-55 alloy 600
- MRP-115 alloy 182/132

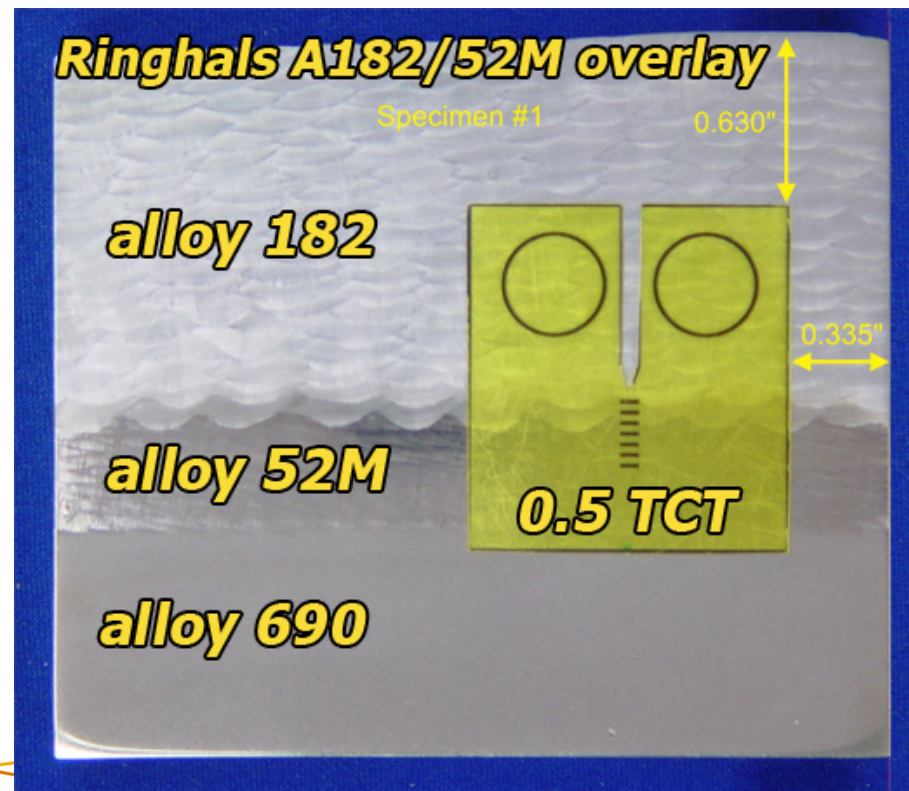
▶ ~15x range of CGRs for various alloy 152/52/52M welds.

▶ All but one show low CGRs, $\leq 5 \times 10^{-9}$ mm/s

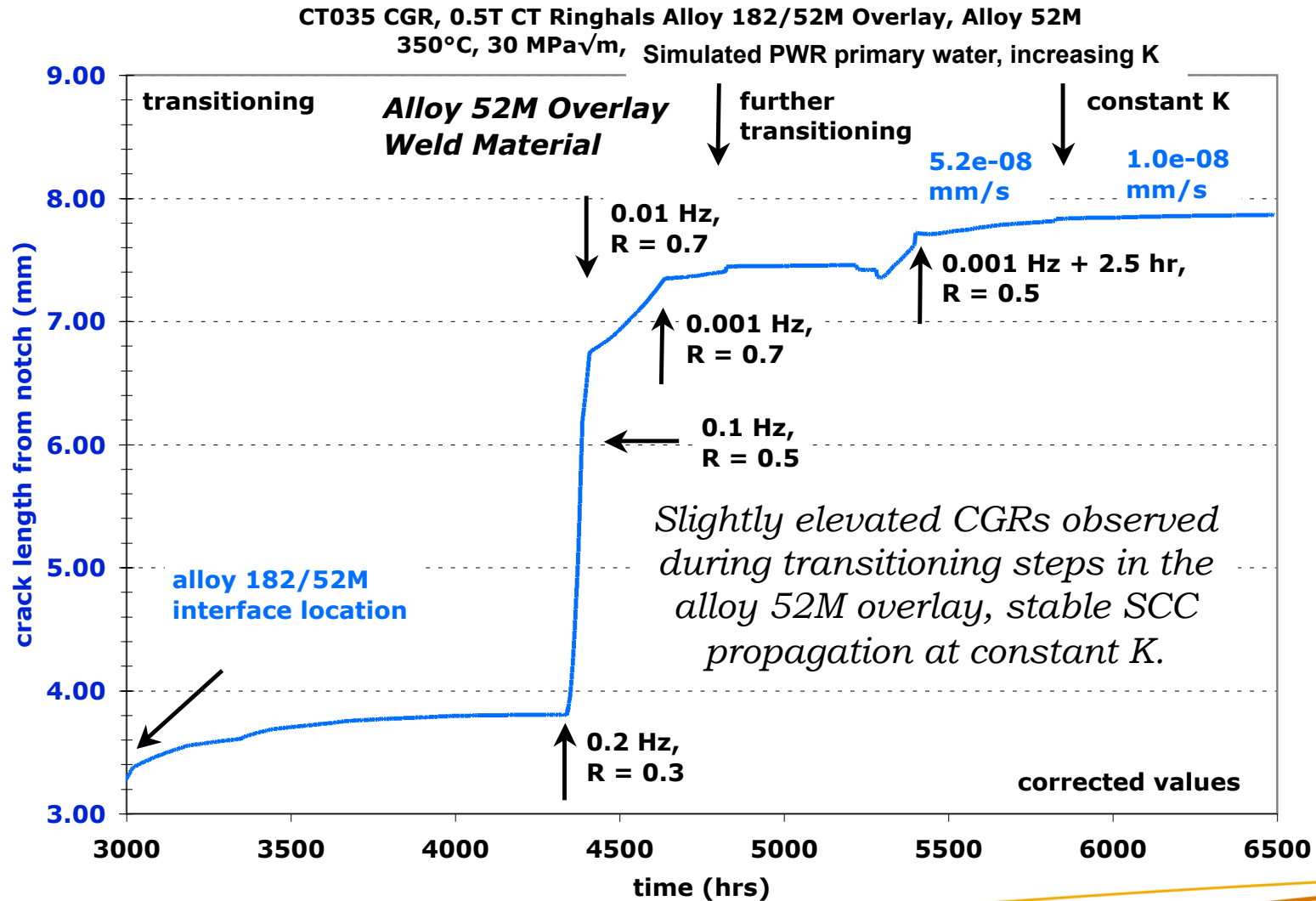
New post-test characterization results on the alloy 52M tests with the two highest crack growth rates.

Alloy 182/52M Ringhals Overlay Mockup

- ▶ Main part of test evaluated SCC growth from alloy 182 into the alloy 52M interface.
- ▶ Crack was advanced by aggressive cycling after ~4400 h and the alloy 52M crack growth response was measured at 350°C, 20 cc/kg H₂ (Ni/NiO line).



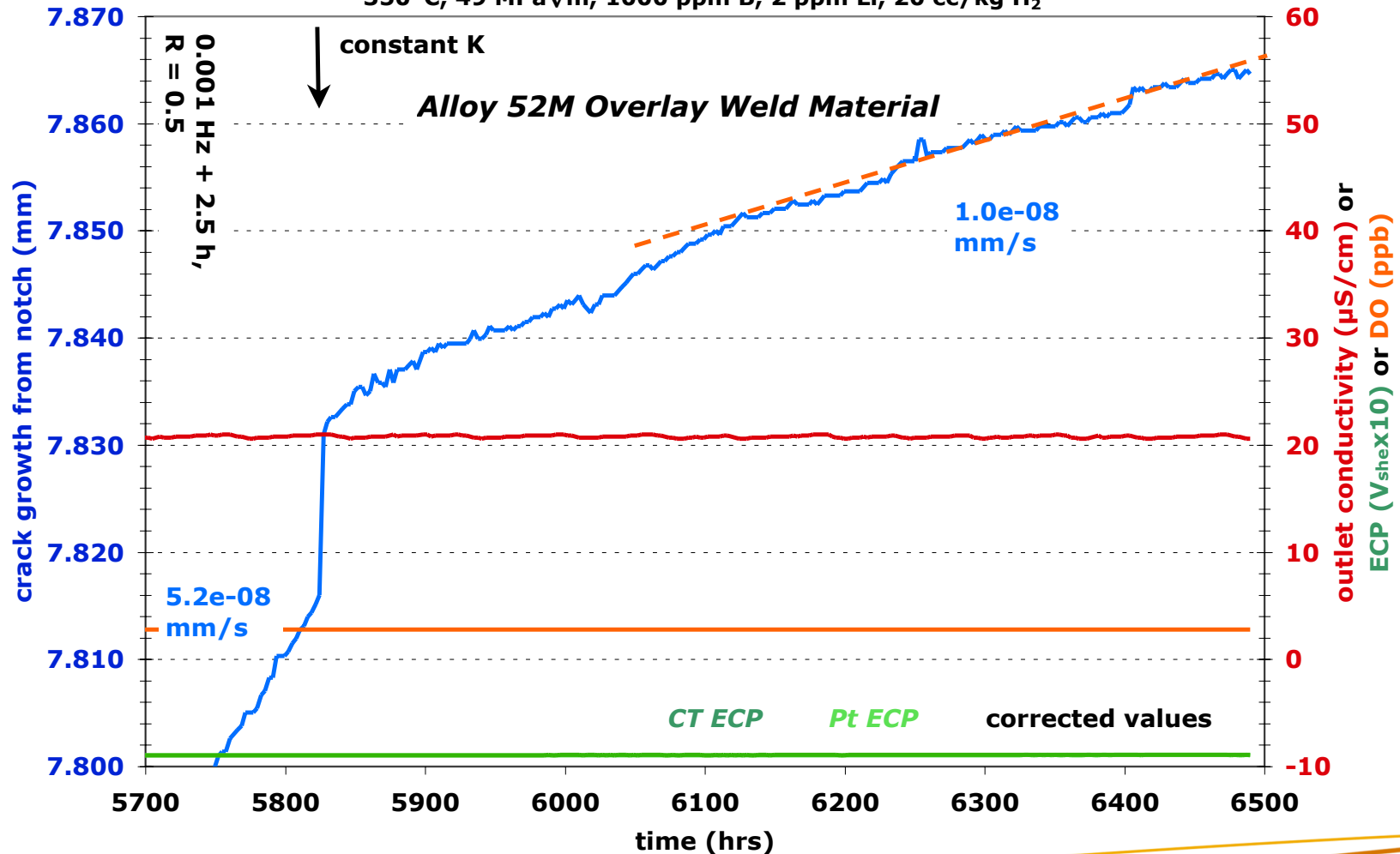
Ringhals Alloy 182/52M Overlay Mockup: Alloy 52M



Crack rapidly advanced deep into alloy 52M weld material starting at about 4350 hours. Various transitioning steps performed, eventually reaching constant K.

Ringhals Alloy 182/52M Overlay Mockup: Alloy 52M Constant K

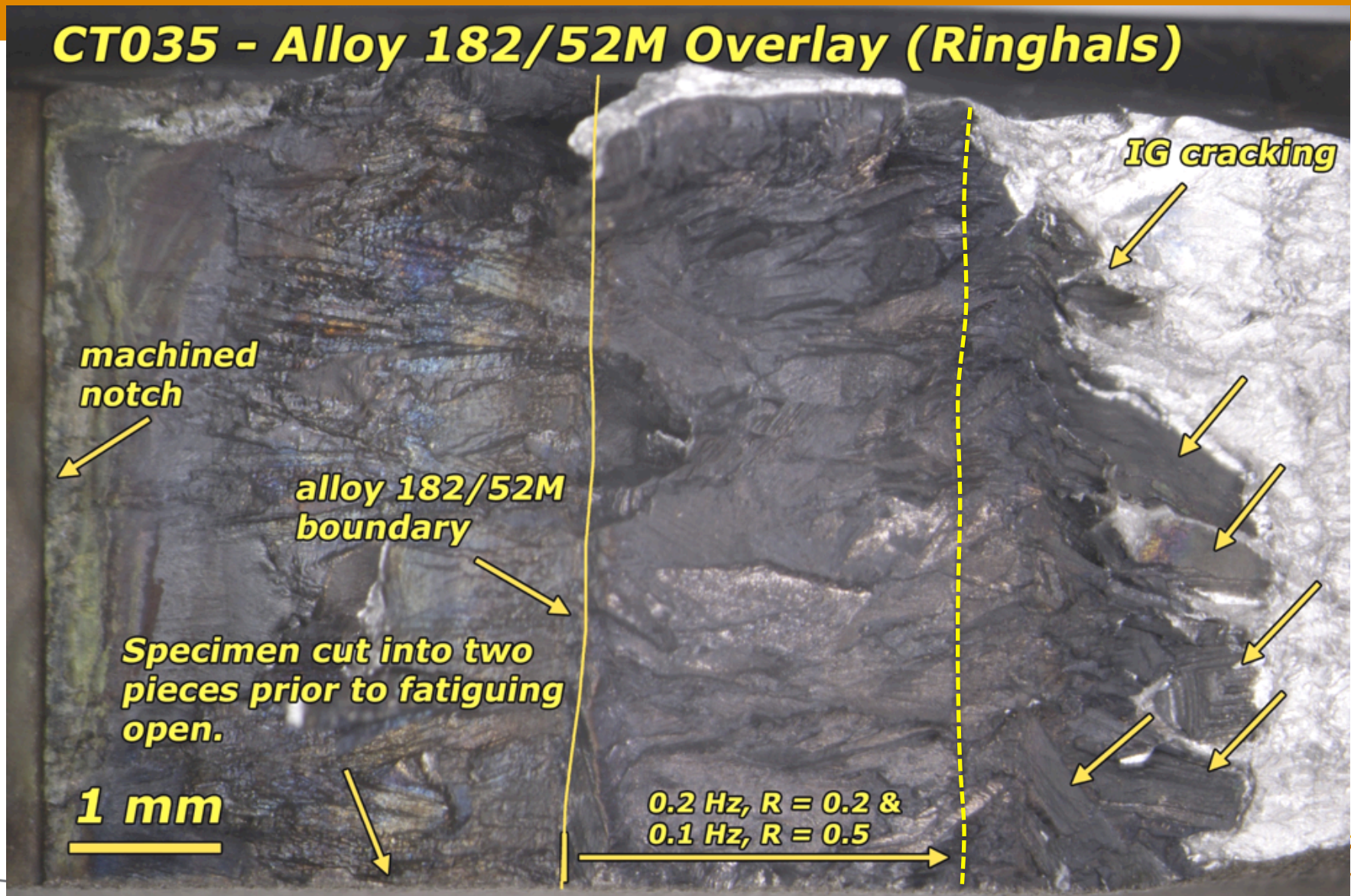
CT035 CGR, 0.5T CT Ringhals Alloy 182/52M Overlay, Alloy 182->52M Traverse
350°C, 49 MPa√m, 1000 ppm B, 2 ppm Li, 20 cc/kg H₂



Rate of $\sim 1 \times 10^{-8}$ mm/s observed over ~ 700 hours at high K value.

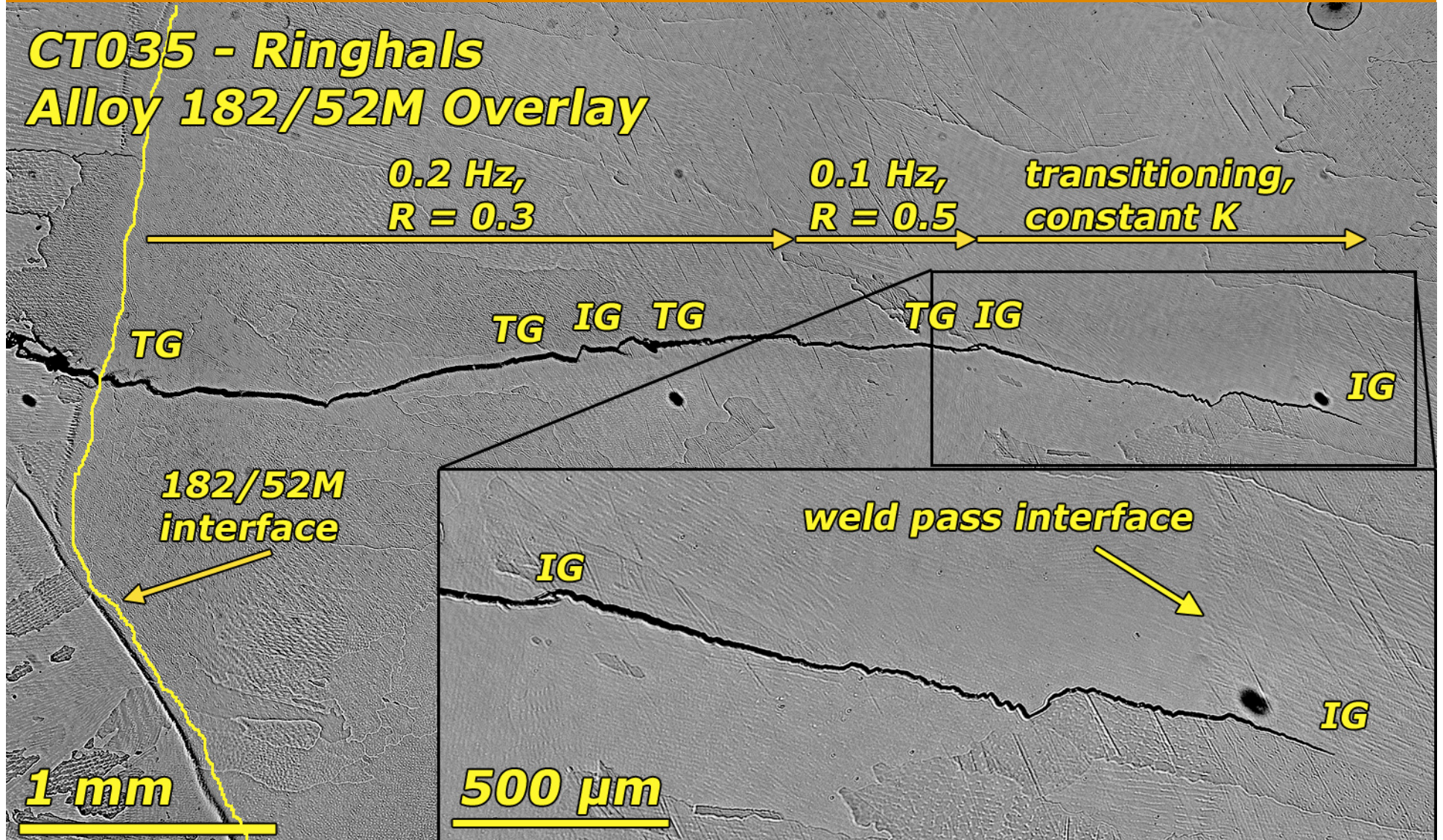
IGSCC in Alloy 52M Overlay Mockup

CT035 - Alloy 182/52M Overlay (Ringhals)



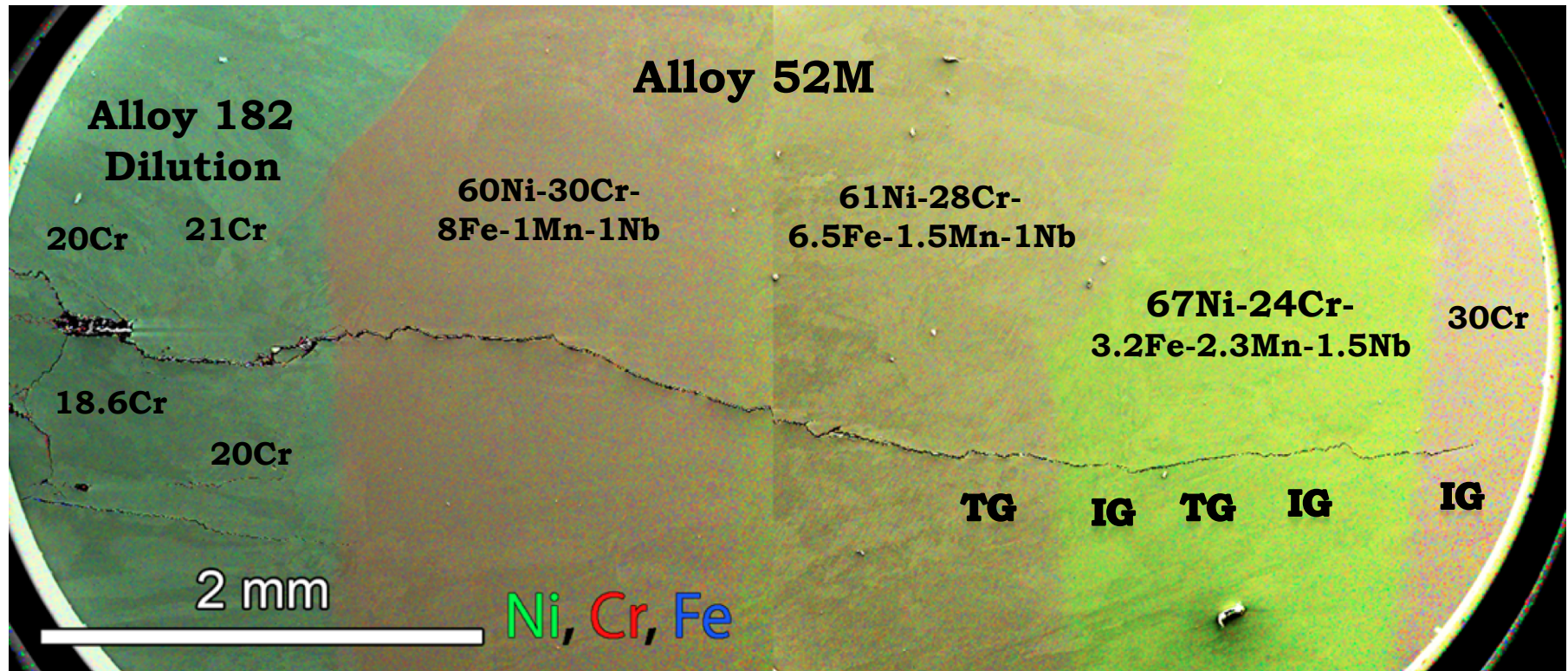
Extensive IG cracking in the final ~1-1.5 mm of SCC testing (transitioning and constant K).

IGSCC in Alloy 52M Overlay Mockup Side Surface Optical



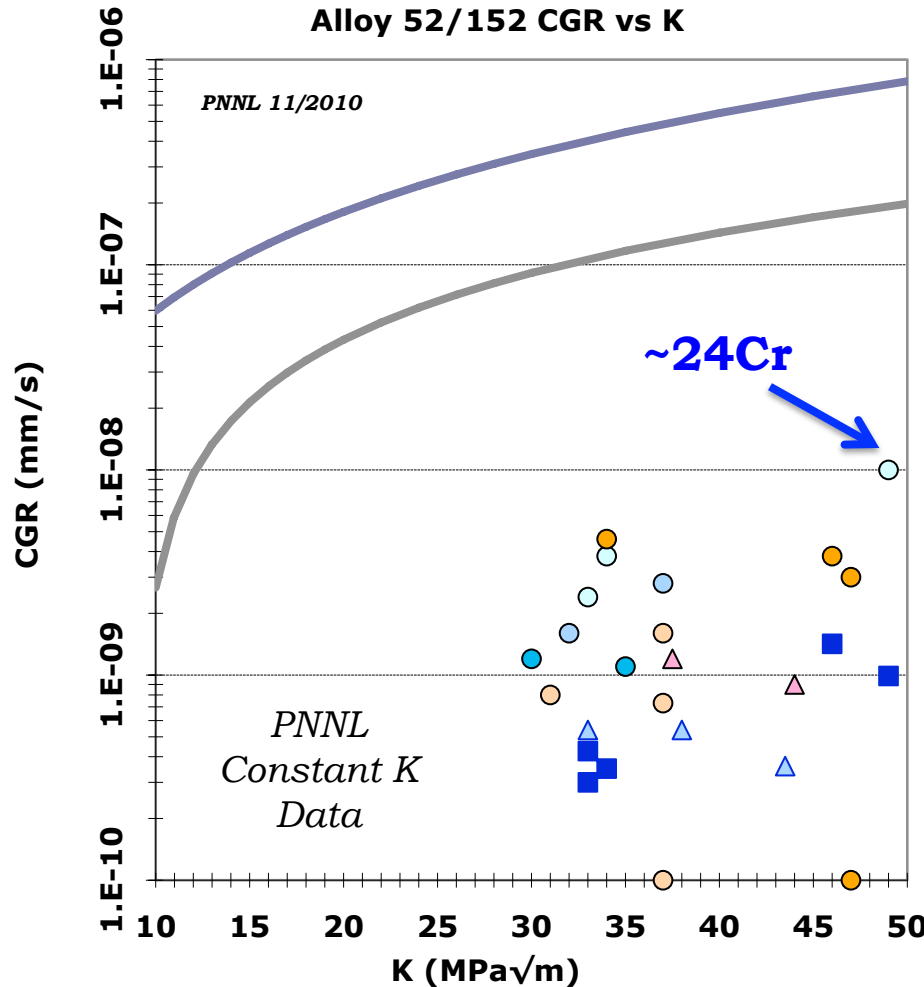
IG cracking in final ~1-1.5 mm confirmed in side surface examination.

IGSCC in Alloy 52M Overlay Mockup Side Surface Weld Layer Compositions



SEM-EDS examination of side surface reveals a weld layer (not just a single weld pass) with significantly off-normal composition. Cr level drops to 24%, most IG cracking corresponds to this weld pass but SCC =
- propagates into the 30% Cr layer at several locations across the front.

Summary of Alloy 152/52/52M SCC Growth Rates at PNNL



- alloy 152 MHI (PNNL)
- △ alloy 52 MHI (PNNL)
- ▲ alloy 52 AREVA (PNNL)
- alloy 52M Ringhals Inlay (PNNL)
- alloy 52M Ringhals Overlay (PNNL)
- alloy 52M VG KAPL (PNNL)
- alloy 52M NG KAPL (PNNL)
- alloy 52M NG HC aligned KAPL (PNNL)
- alloy 52M NG HC non-aligned KAPL (PNNL)
- MRP-55 alloy 600
- MRP-115 alloy 182/132

▶ ~15x range of CGRs for various alloy 152/52/52M welds.

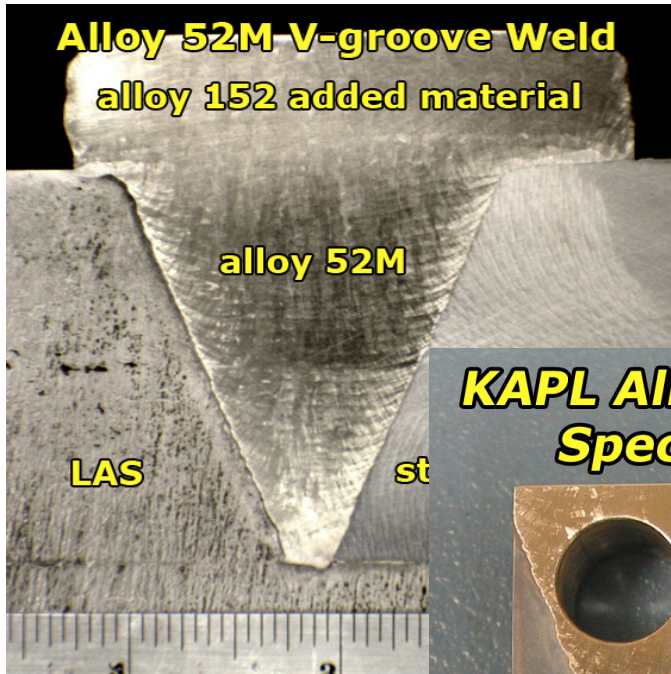
▶ Highest value of $\sim 1 \times 10^{-8}$ mm/s corresponds to weld overlay layer with off-normal composition and high K.

PNNL Weld Metal SCC Crack-Growth Testing Summary

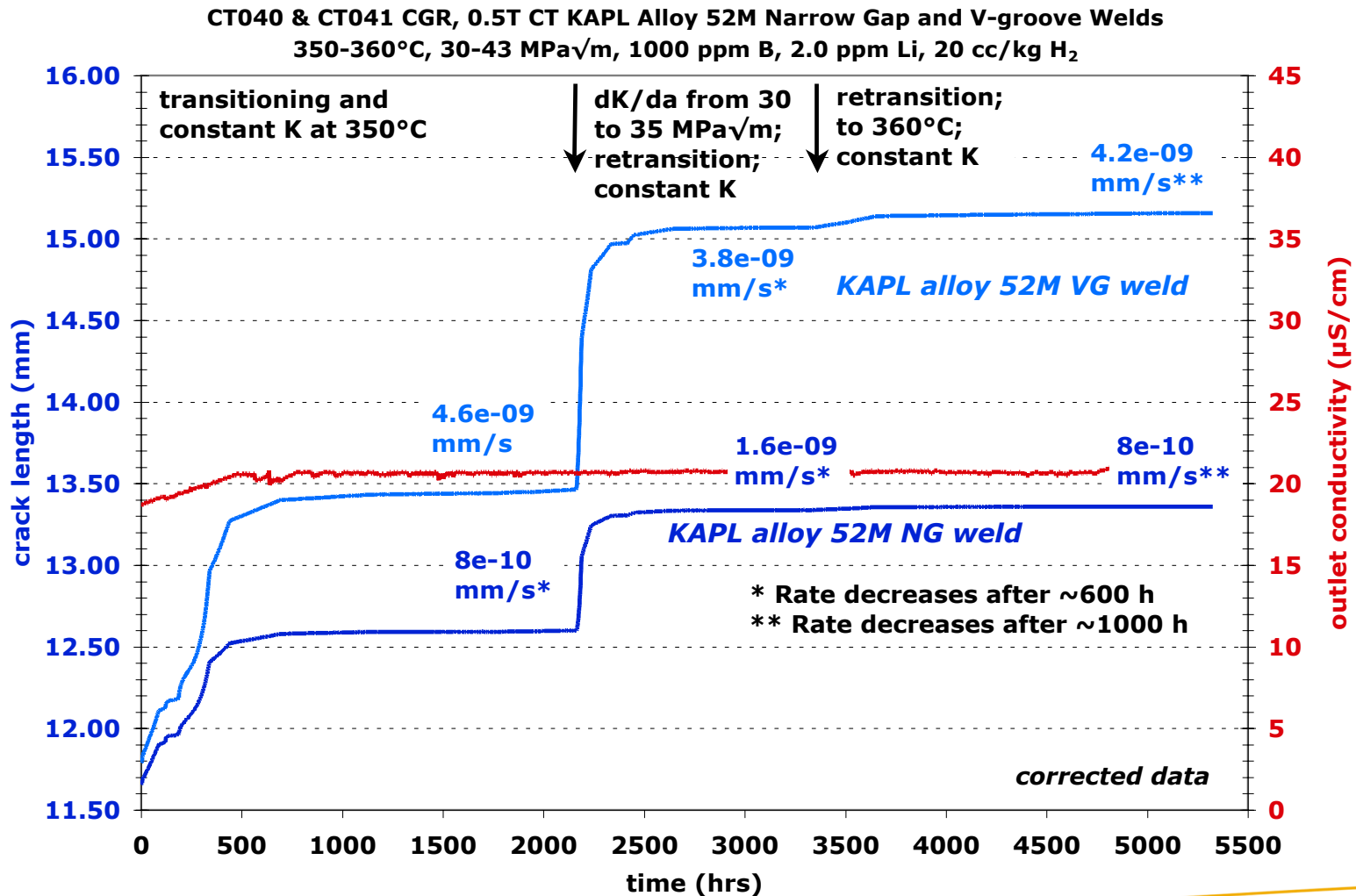
- ▶ *Alloy 52 Mockup Welds*
 - *2 tests on an MHI U-groove weld*
 - *2 test on an AREVA butt weld*
- ▶ *Alloy 52M Inlay & Overlay Mockup Welds*
 - *3 tests on Ringhals overlay, new post test analysis*
 - *2 tests on Ringhals inlay*
- ▶ *Alloy 52M Mockup Welds*
 - *1 test on KAPL V-groove weld, **new post test analysis***
 - *1 test on KAPL narrow gap weld*
 - *2 tests on KAPL NG weld with hot cracks*
- ▶ *Alloy 52MSS Mockup Weld*
 - ***Ongoing test on Special Metals weld***
- ▶ *Alloy 152 Mockup Welds*
 - *3 tests on an MHI U-groove weld (one with LAS SR)*
 - ***Ongoing tests on ANL V2 weld and 20%CF MHI weld***

Alloy 52M KAPL V-Groove and Narrow Gap Welds

- ▶ *Fabricated at KAPL from the same wire (NX5285TK)*
- ▶ *Data obtained at*
 - 350°C, 20 cc/kg H₂ (Ni/NiO line)
 - 360°C, 25 cc/kg H₂ (Ni/NiO line)



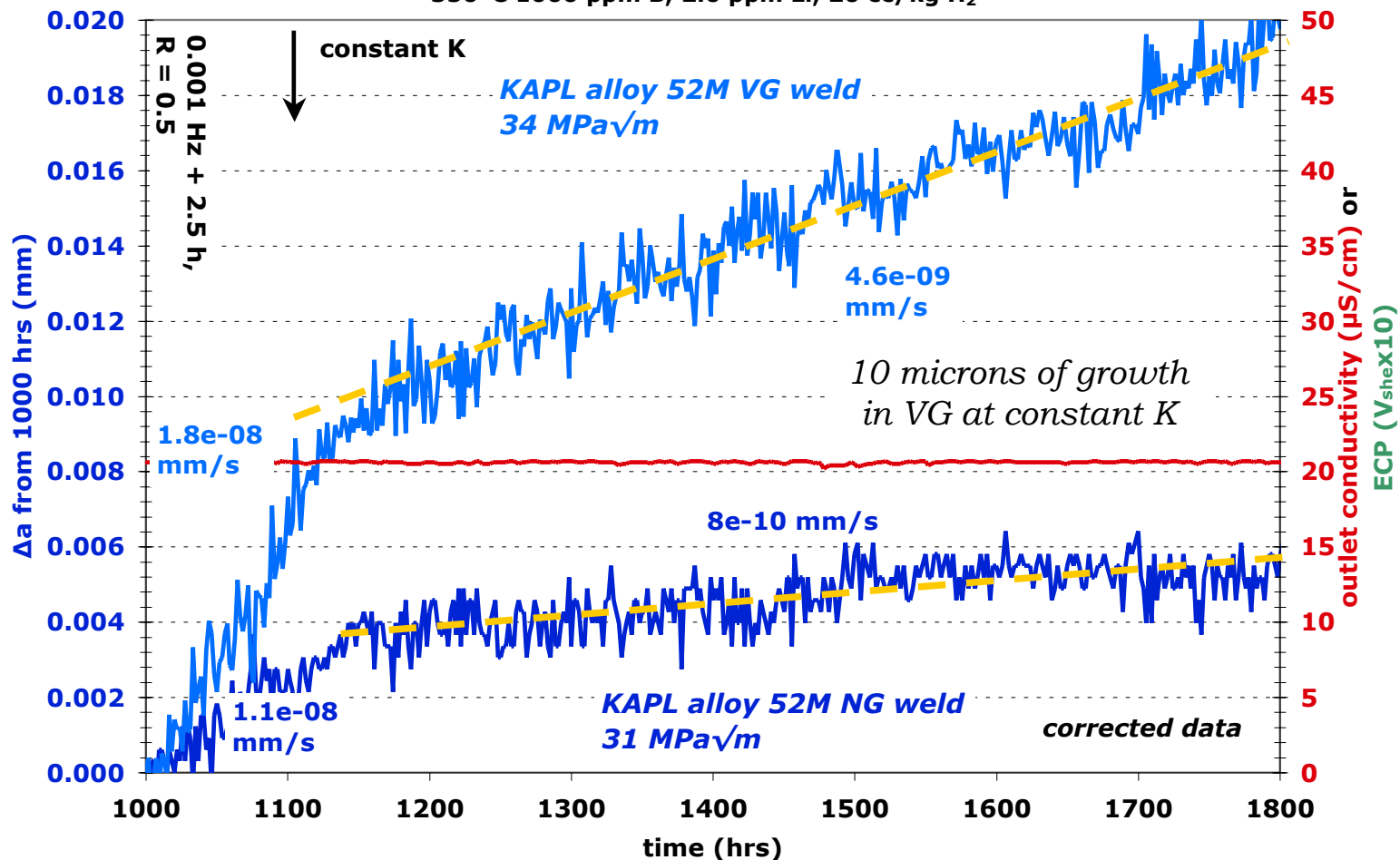
Alloy 52M V-Groove and Narrow Gap Mockup Welds (KAPL): Overview



Consistently higher crack-growth rate in the V-groove weld

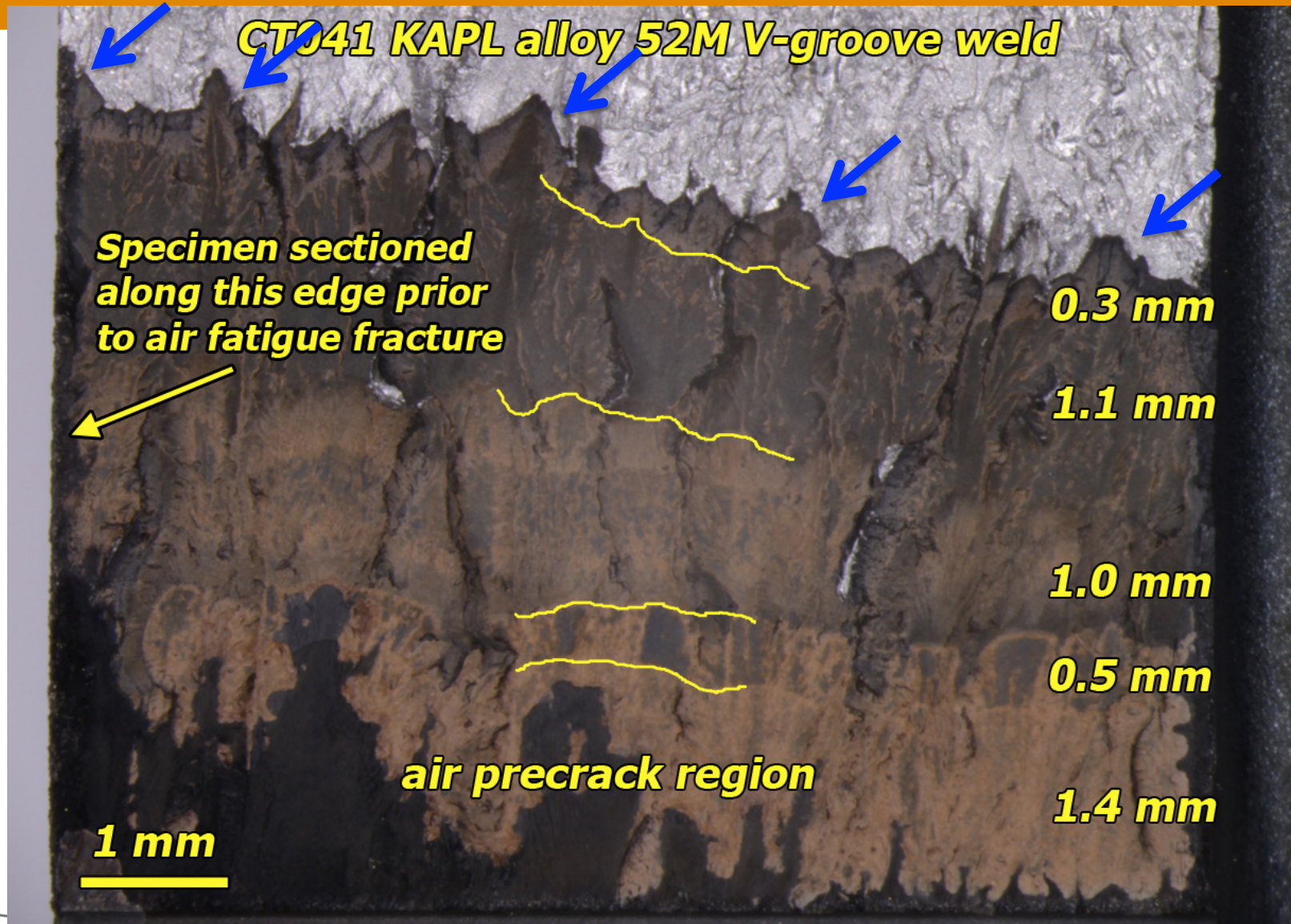
Alloy 52M V-Groove and Narrow Gap Mockup Welds (KAPL): Constant K

CT040 & CT041 CGR, 0.5T CT KAPL Alloy 52M Narrow Gap and V-groove Welds
350°C 1000 ppm B, 2.0 ppm Li, 20 cc/kg H₂



Consistently higher crack-growth rate in the V-groove weld

IGSCC in Alloy 52M V-Groove Weld



Undulating crack front with many areas of IG cracking.

IGSCC in Alloy 52M V-Groove Weld Side Surface Optical

CT041 - KAPL alloy 52M V-groove weld

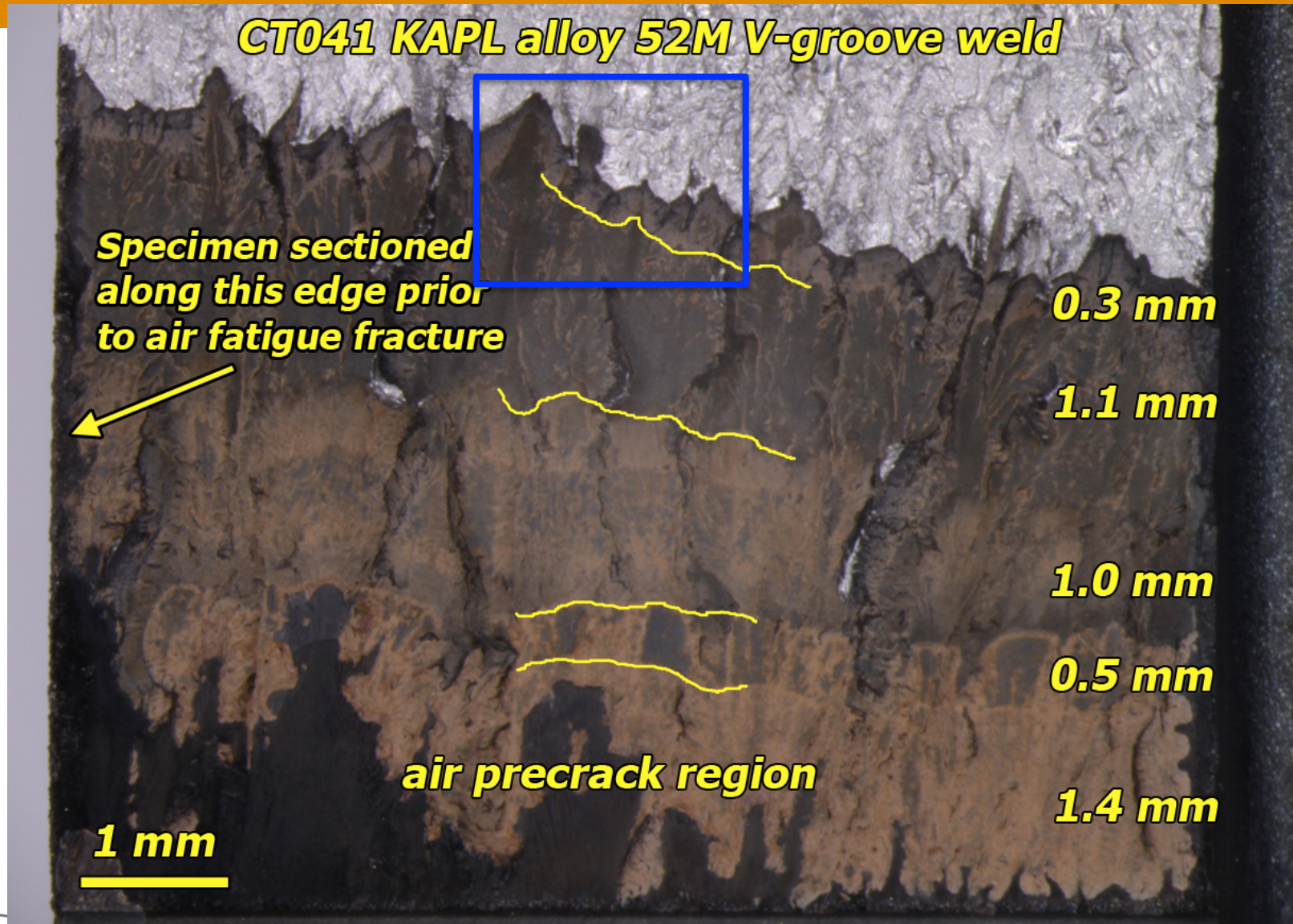
begin mixed IG and TG extension

precracking ends in
the middle of a grain

500 μ m

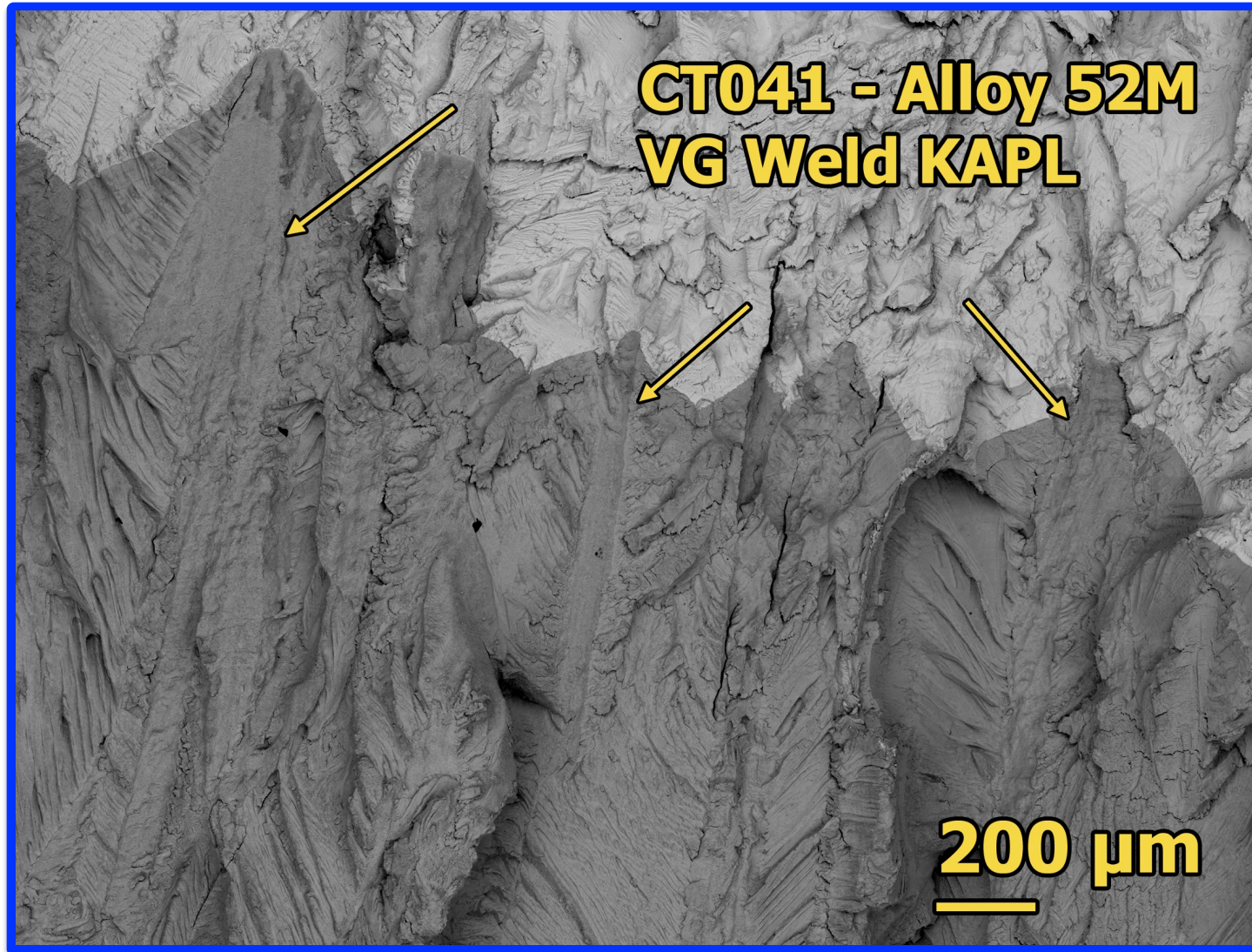
- ▶ Long narrow boundaries in region of the crack.
- ▶ Boundaries are well aligned with direction of cracking.
- ▶ Crack intersects and mostly stays on a grain boundary for ~ 2 mm of growth on this side surface.
- ▶ Constant K CGR of $2.8-4.6 \times 10^{-9}$ mm/s.

IGSCC in Alloy 52M V-Groove Weld



Undulating crack front with many areas of IG cracking.

IGSCC in Alloy 52M V-Groove Weld Crack Surface SEM



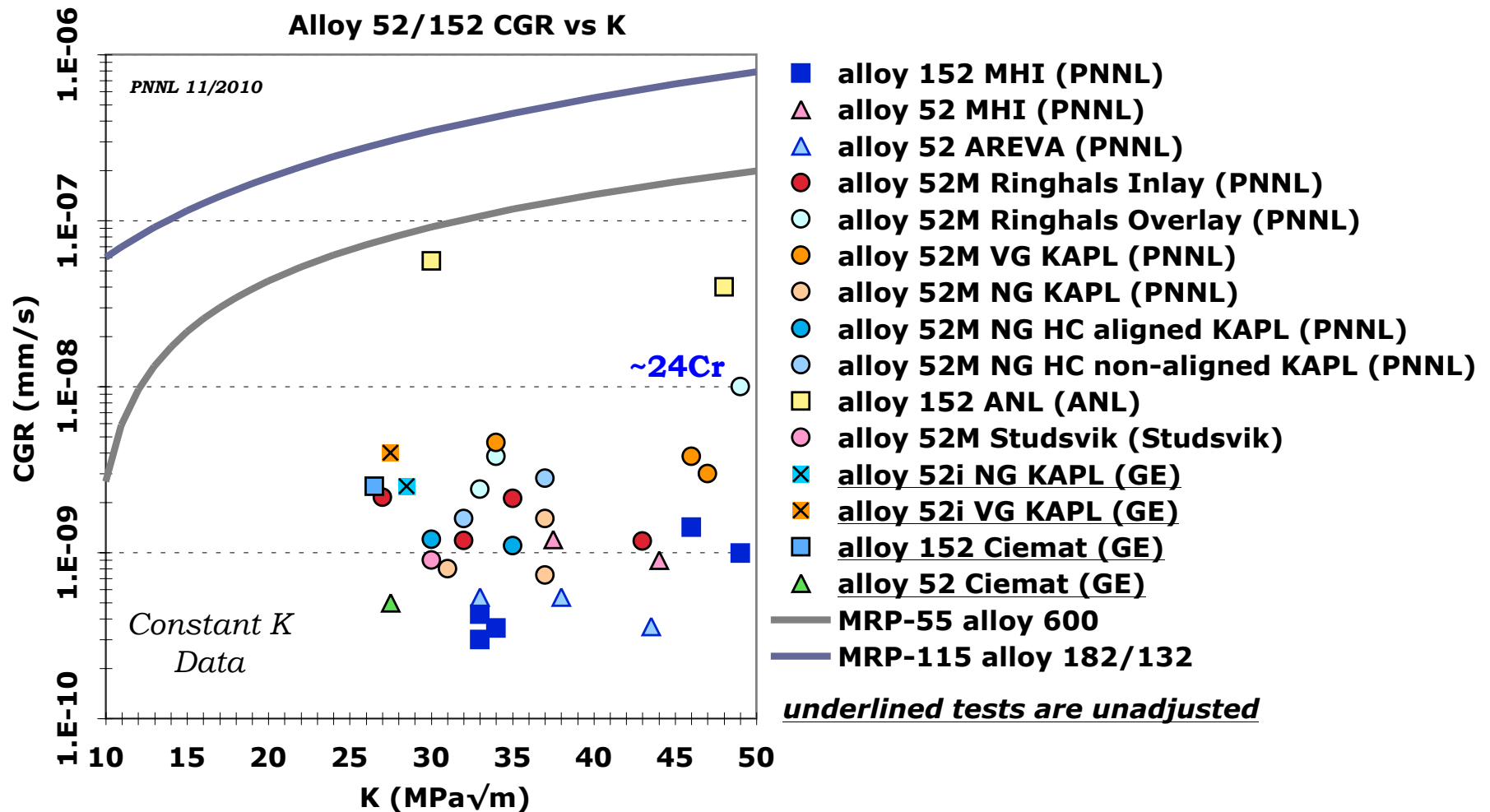
Protusions are IGSCC in the middle and flanked by TG cracking, estimated “maximum local” IGSCC rate of $\sim 2 \times 10^{-8}$ mm/s.

Alloy 152/52/52M Summary

- ▶ IGSCC crack advance observed in nearly all alloy 152/52/52M weld metals in 350-360°C simulated primary PWR primary water. However, only partial IG engagement is observed resulting in average growth rates of $\leq 5 \times 10^{-9}$ mm/s for prototypic compositions.
- ▶ Some preference for IG cracking, but not strong. Maximum IGSCC growth rates in local engaged “fingers” may be 3-5x higher than average rates.
- ▶ Highest weld crack growth rate measured at PNNL was in an overlay layer with off-normal (Cr level at ~24 wt%) composition.



Summary of Alloy 152/52/52M SCC Growth Rates



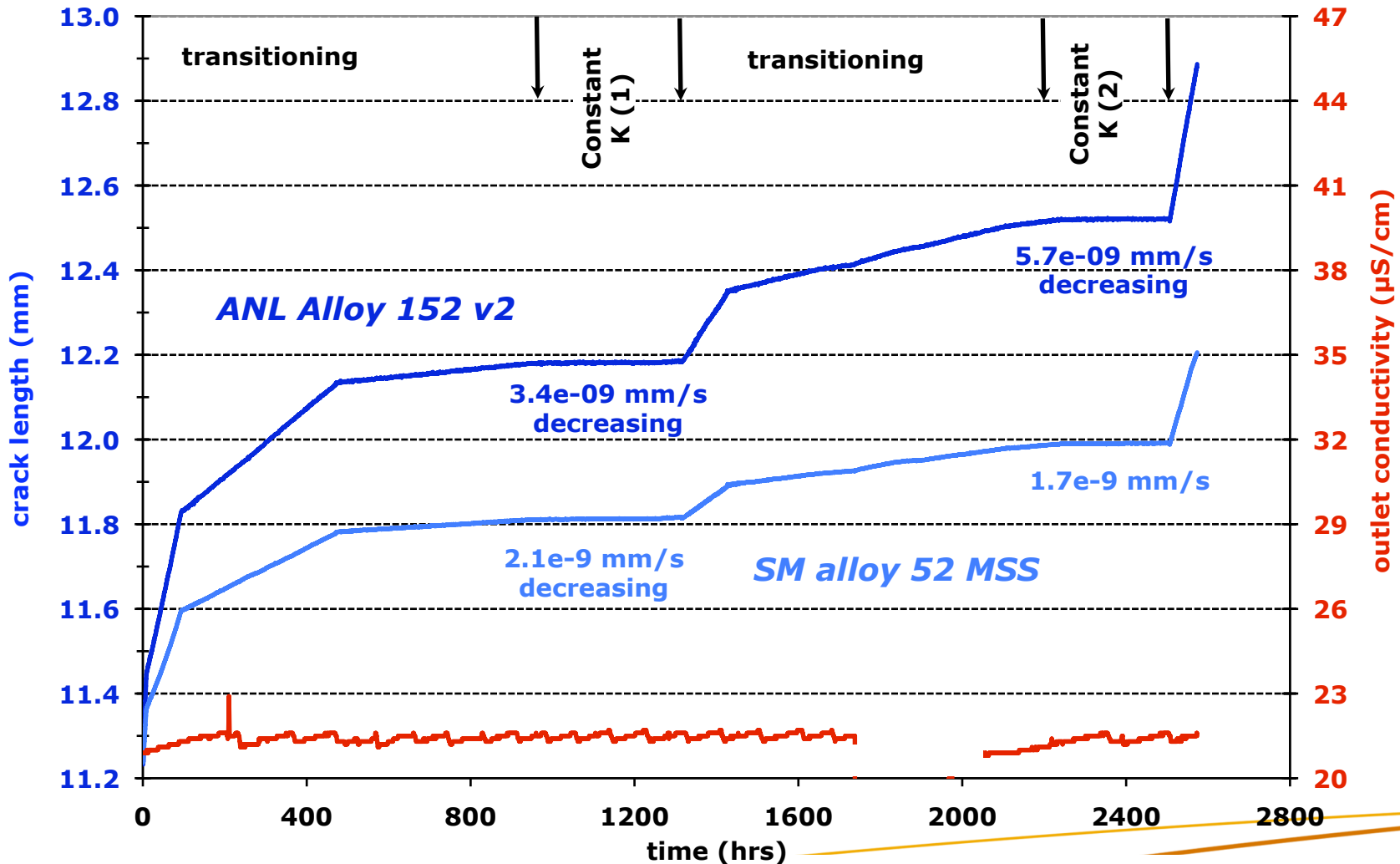
Nearly all weld data (on completed tests) have shown
SCC propagation rates below $\sim 5 \times 10^{-9}$ mm/s.

PNNL Weld Metal SCC Crack-Growth Testing Summary

- ▶ *Alloy 52 Mockup Welds*
 - *2 tests on an MHI U-groove weld*
 - *2 test on an AREVA butt weld*
- ▶ *Alloy 52M Inlay & Overlay Mockup Welds*
 - *3 tests on Ringhals overlay, new post test analysis*
 - *2 tests on Ringhals inlay*
- ▶ *Alloy 52M Mockup Welds*
 - *1 test on KAPL V-groove weld, new post test analysis*
 - *1 test on KAPL narrow gap weld*
 - *2 tests on KAPL NG weld with hot cracks*
- ▶ *Alloy 52MSS Mockup Weld*
 - ***Ongoing test on Special Metals weld***
- ▶ *Alloy 152 Mockup Welds*
 - *3 tests on an MHI U-groove weld (one with LAS SR)*
 - ***Ongoing tests on ANL V2 weld and 20%CF MHI weld***

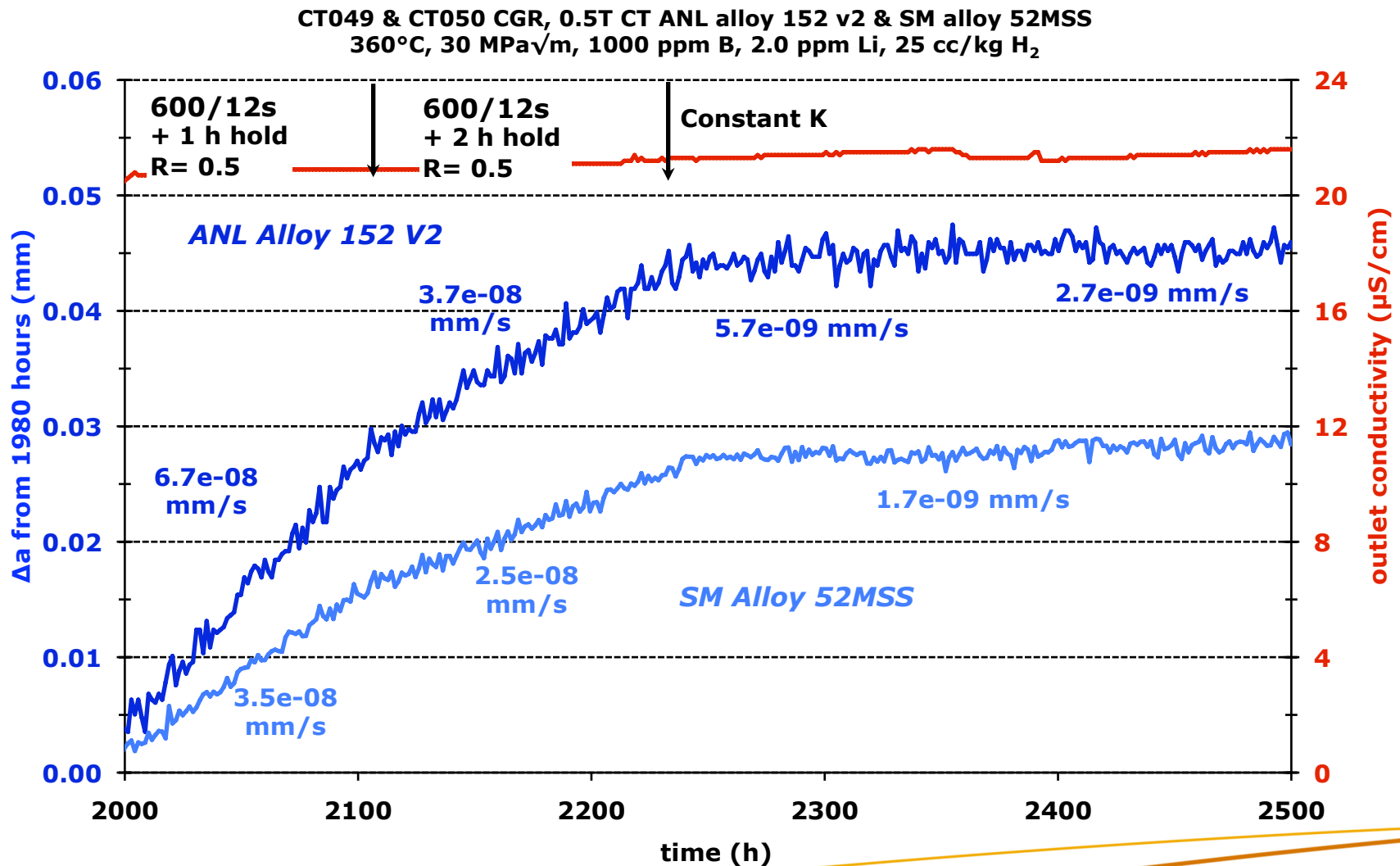
Overview of ANL Alloy 152 V2 and SM Alloy 52MSS Welds - Ongoing

CT049 & CT050 CGR, 0.5T CT ANL alloy 152 v2 & SM alloy 52 MSS
 360°C, 30 MPa√m, 1000 ppm B, 2.0 ppm Li, 25 cc/kg H₂



Two transitioning and constant *K* attempts so far, low SCC growth rates. Currently moving to new microstructural region.

Overview of ANL Alloy 152 V2 and SM Alloy 52MSS Welds - Ongoing (2)

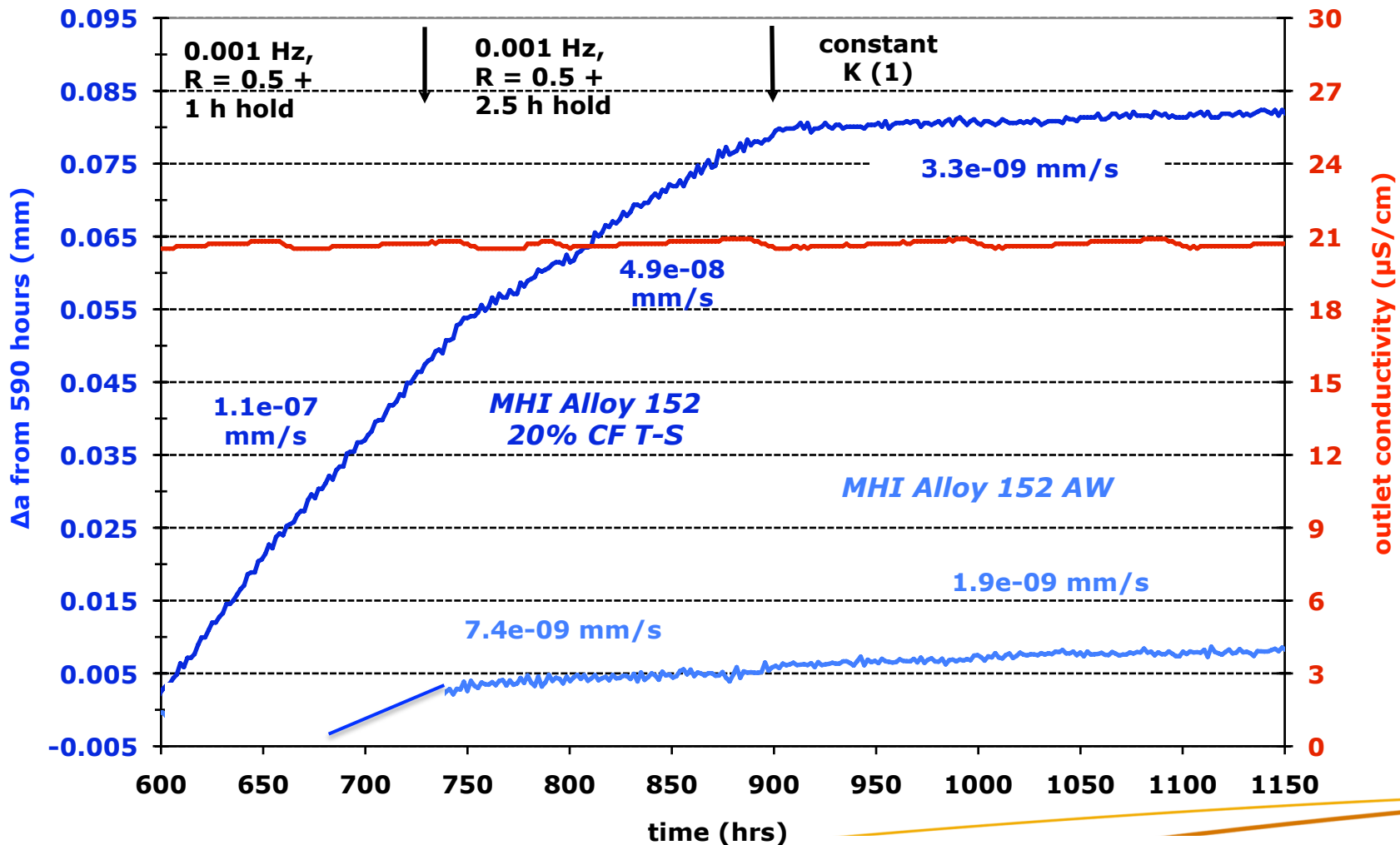


Second attempt examining constant K response after alternative transitioning. Higher cycle + hold growth rates for 152, but again low constant K rates.

Cold Forged MHI Alloy 152

Evaluation of Simulated High Strain Weld

CT051 & CT052 CGR, 0.5T CT MHI alloy 152 20%CF T-S and as-welded
 360°C, 30 MPa√m, 1000 ppm B, 2.0 ppm Li, 25 cc/kg H₂

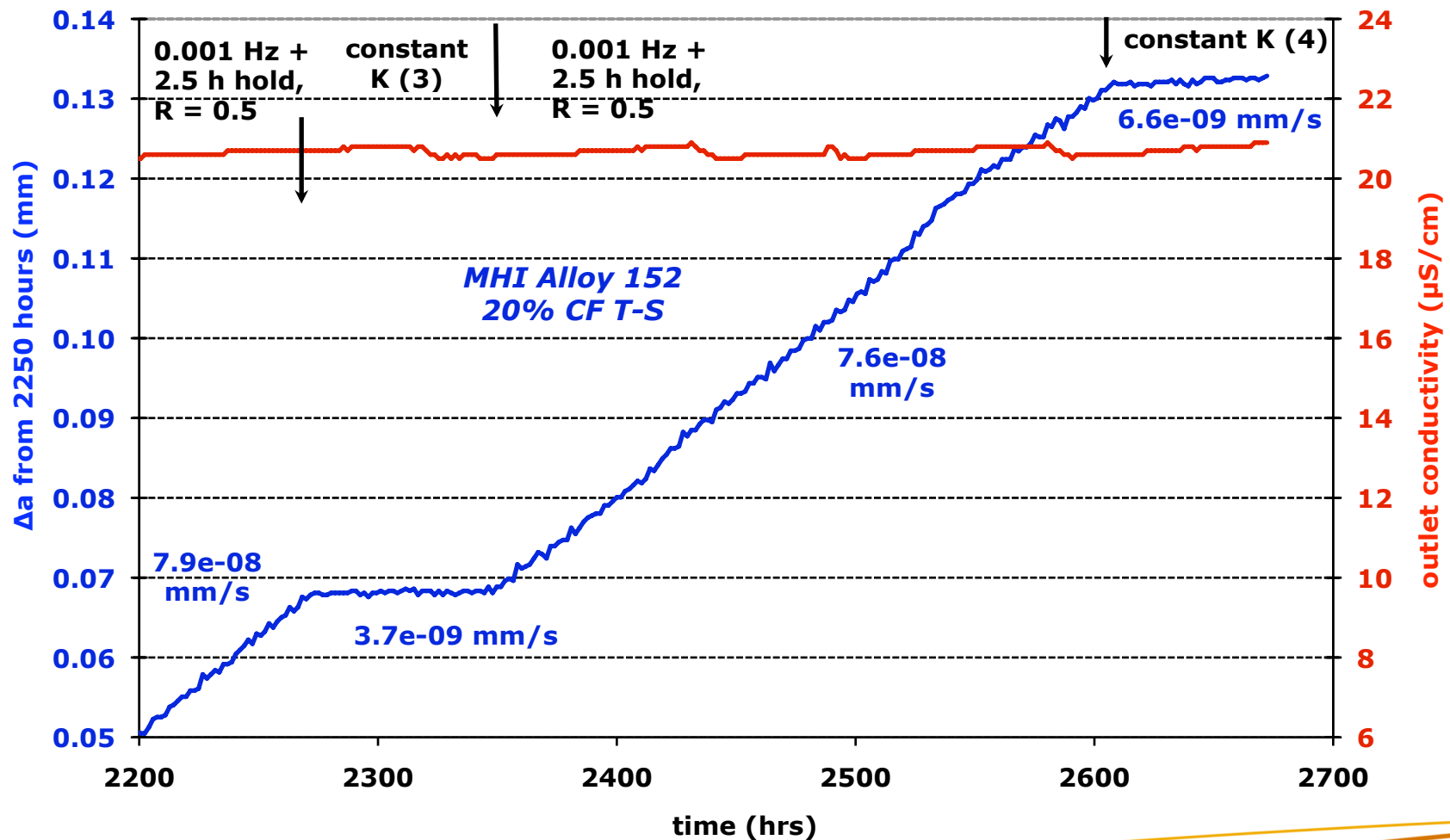


Cold forged MHI alloy 152 weld shows higher propagation rates during cycle + hold transitioning, but low constant K rates.

Cold Forged MHI Alloy 152

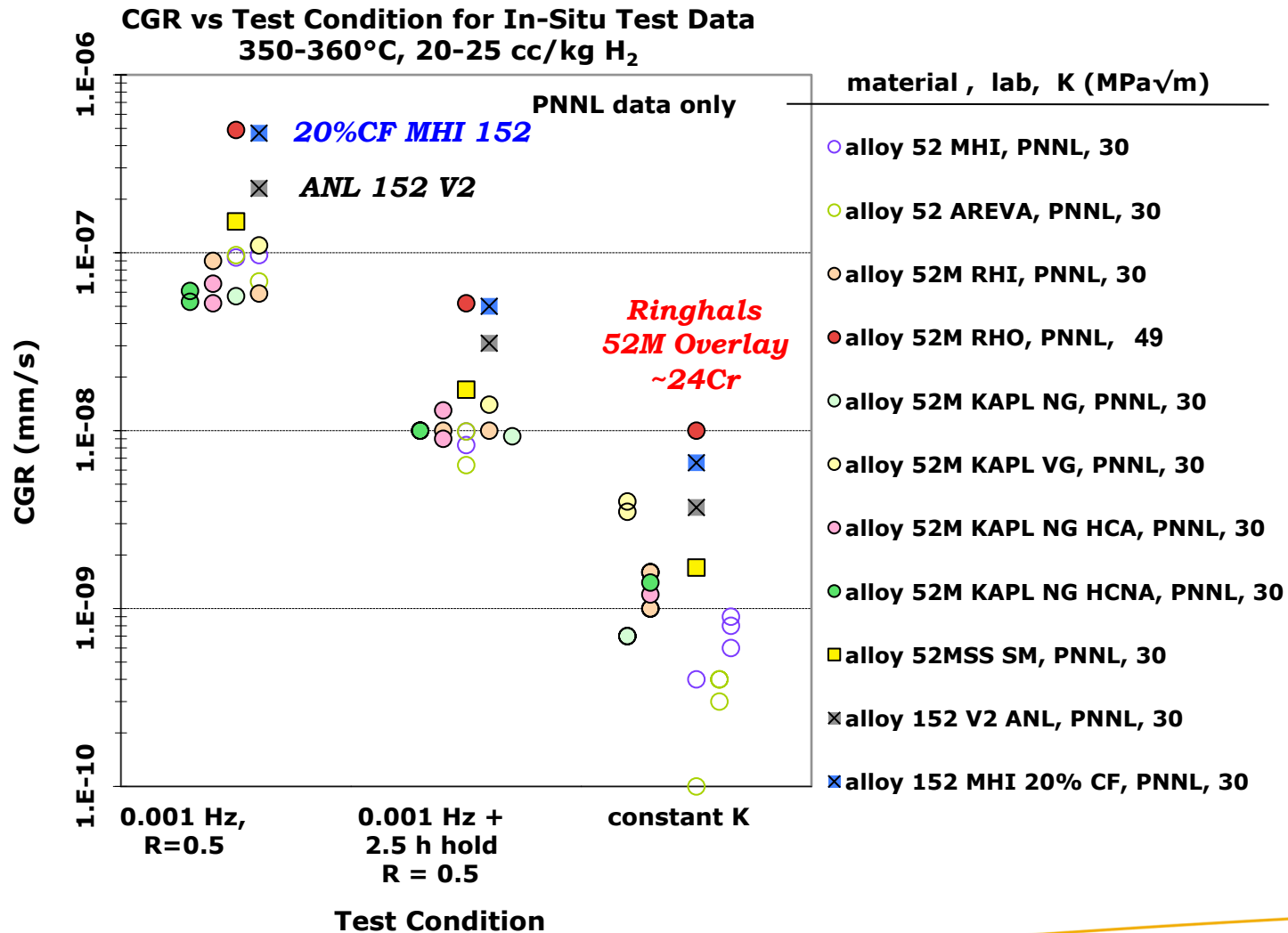
Evaluation of Cold Work Effects

CT051 & CT052 CGR, 0.5T CT MHI alloy 152 20%CF T-S and as-welded
 360°C, 30 MPa√m, 1000 ppm B, 2.0 ppm Li, 25 cc/kg H₂



Cold forged MHI alloy 152 weld shows higher propagation rates during transitioning, but constant K rates still only $\sim 7 \times 10^{-9}$ mm/s.

Summary of PNNL Alloy 152/52/52M Transitioning and SCC Growth Rates



Consistent final transitioning and constant K response for most welds, slightly higher rates for 20%CF MHI and ANL V2 alloy 152.

PNNL Weld Metal SCC Crack-Growth Summary of Ongoing Tests

▶ **ANL Alloy 152 V2 Mockup Weld**

- Somewhat higher ($\sim 2X$) cycle + hold crack growth rates than for other alloy 152/52/52M weld metals
- Low and decreasing SCC growth rates (stable rate of $\sim 3 \times 10^{-9}$ mm/s) during constant K loading indicates limited engagement

▶ **20%CF MHI Alloy 152 Mockup Weld**

- Consistently higher (3-4X) cycle + hold crack growth rates than for other alloy 152/52/52M weld metals
- However so far, SCC growth rates at constant K only reach $\sim 7 \times 10^{-9}$ mm/s.

▶ **Special Metals Alloy 52MSS Mockup Weld**

- Low cycle + hold and constant K crack growth rates, suggests limited SCC engagement.
- Stable constant K propagation rate of $\sim 2 \times 10^{-9}$ mm/s.



PNNL Weld Metal SCC Crack-Growth *Near Term Dilution Zone Test Plans*

Weldment	Material Condition	Purpose	Estimated Test Date
KAPL Alloy 152/LAS Mock-Up DM Weld	As welded	Evaluate alloy 152 - LAS dilution zone susceptibility	2011-12
ANL Alloy 152/LAS Mock-Up DM Weld	As welded	Evaluate alloy 152 - LAS dilution zone susceptibility	2011-12
MHI Alloy 152/SS Mock-Up DM Weld	As welded	Evaluate alloy 152 - SS dilution zone susceptibility	2012
KAPL Alloy 52M/SS Mock-Up DM Weld	As welded	Evaluate alloy 52M - SS dilution zone susceptibility	2012

PNNL Weld Metal SCC Crack-Growth Near Term HAZ Test Plans

Weldment	Material Condition	Purpose	Estimated Test Date
CIEMAT Alloy 152/690 Mock-Up Weld	As welded	Evaluate HAZ susceptibility	2011-12
CIEMAT Alloy 52/690 Mock-Up Weld	As welded	Evaluate HAZ susceptibility	2011-12
KAPL Alloy 52M/690 Mock-Up Weld	As welded	Evaluate HAZ susceptibility	2012
SM Alloy 52MSS/690 Mock-Up Weld	As welded	Evaluate HAZ susceptibility	2012