INL/CON-22-67994-Revision-0

Effect of Water Chemistry on Crack Growth Rates in Neutron Irradiated X-750 and XM-19

July 2022

Drew Coulson Johnson

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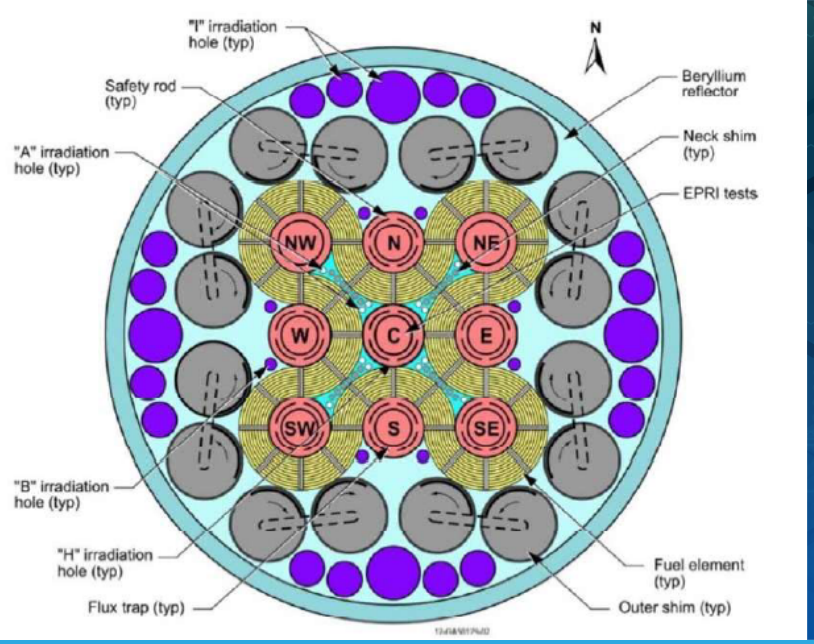
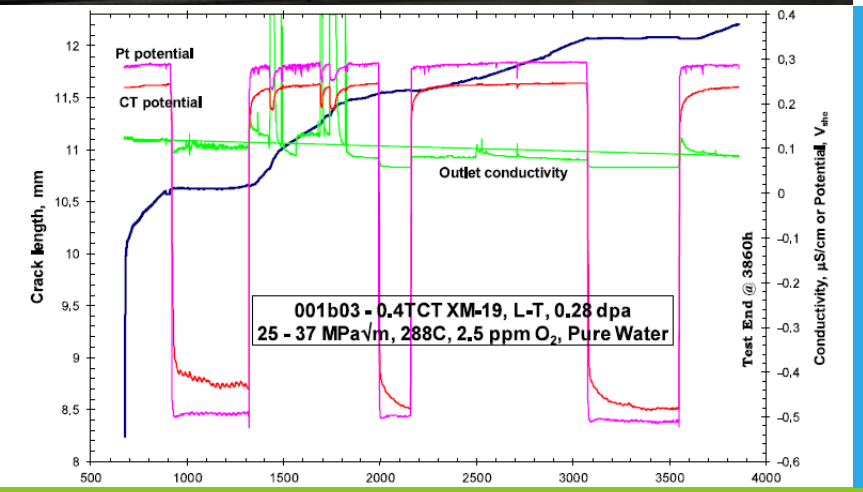


Drew C. Johnson

ENV DEG 2022

Monday July 18th



Effect of Water Chemistry on Crack Growth Rate in Neutron Irradiated X-750 and XM-19

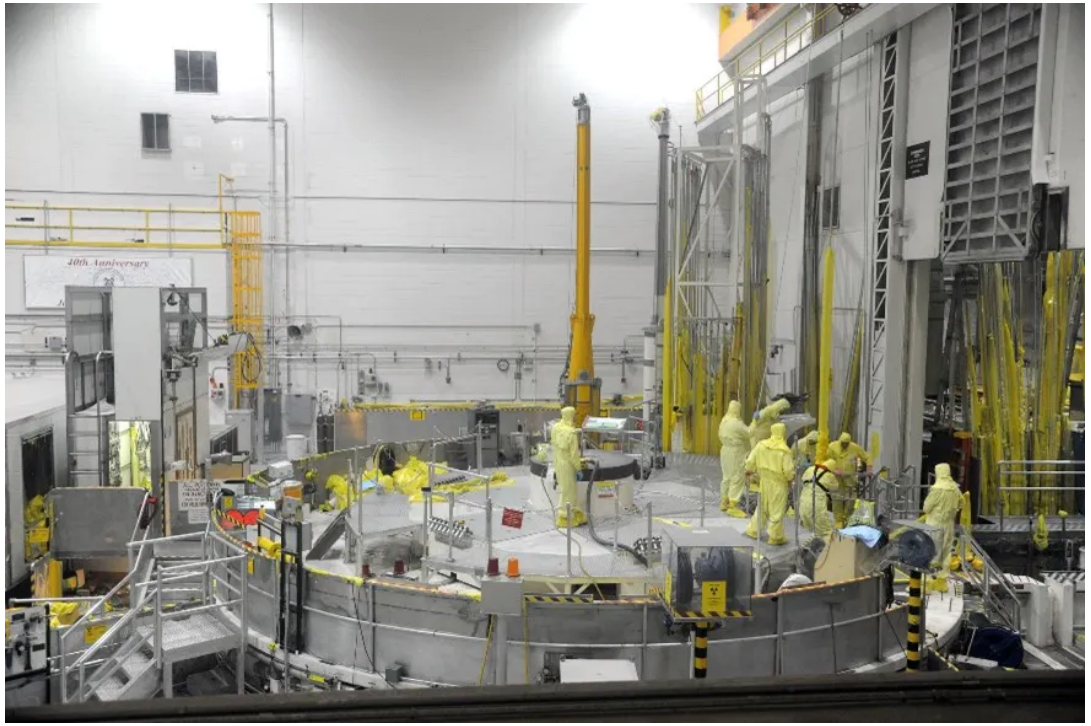
Idaho National Laboratory

Co-authors

- John H. Jackson and Michael Heighes, INL
- Peter L. Andresen, Andresen Consulting/GE Global Research Center (retired)
- Robert Carter, EPRI

Neutron Irradiation and PIE of X-750 and XM-19

- Irradiations conducted at the Advanced Test Reactor (ATR) National Science User Facility (NSUF), utilizing the central flux trap (CFT) position
  - First civilian project to utilize this reactor position
- ~0.3 dpa and ~1.4 dpa samples produced to investigate mid-life and life extension (60-80 yr) behavior



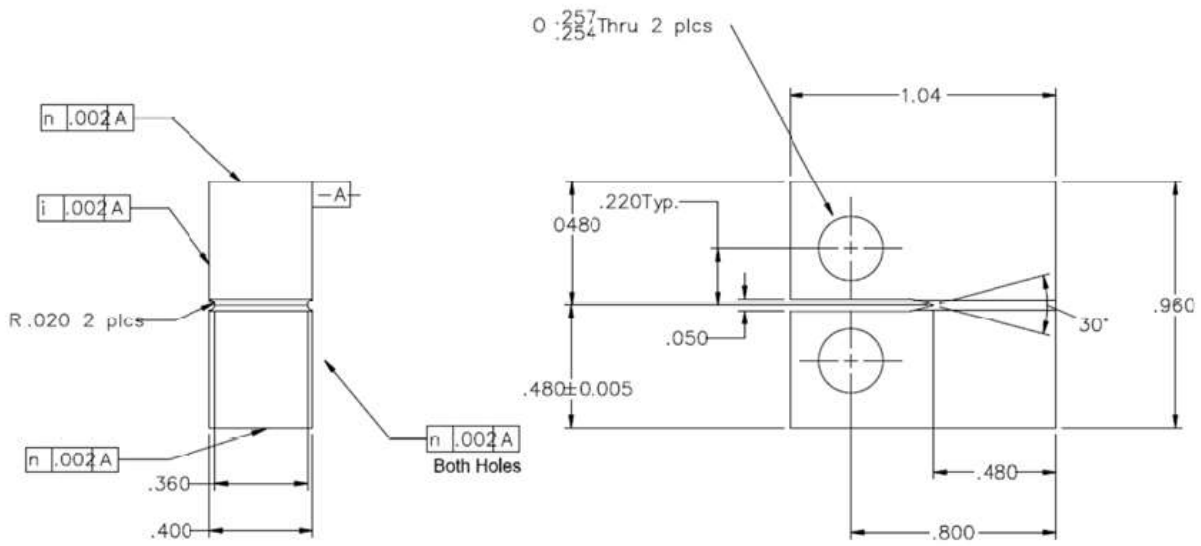
X-750 and XM-19 Samples for CGR Testing

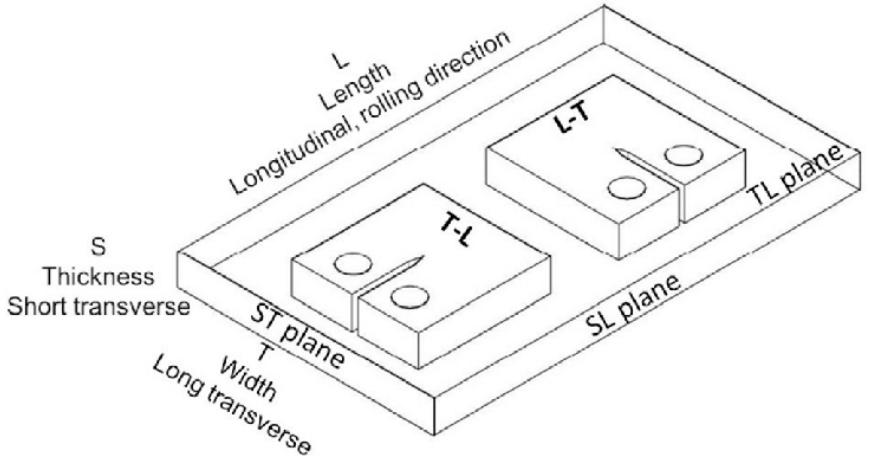
X-750

Element	Al	C	Nb	Co	Cr	Fe	Mn	Ni	Ti
wt%	0.77	0.04	0.97	0.726	14.99	7.8	0.197	70.8	2.42

XM-19

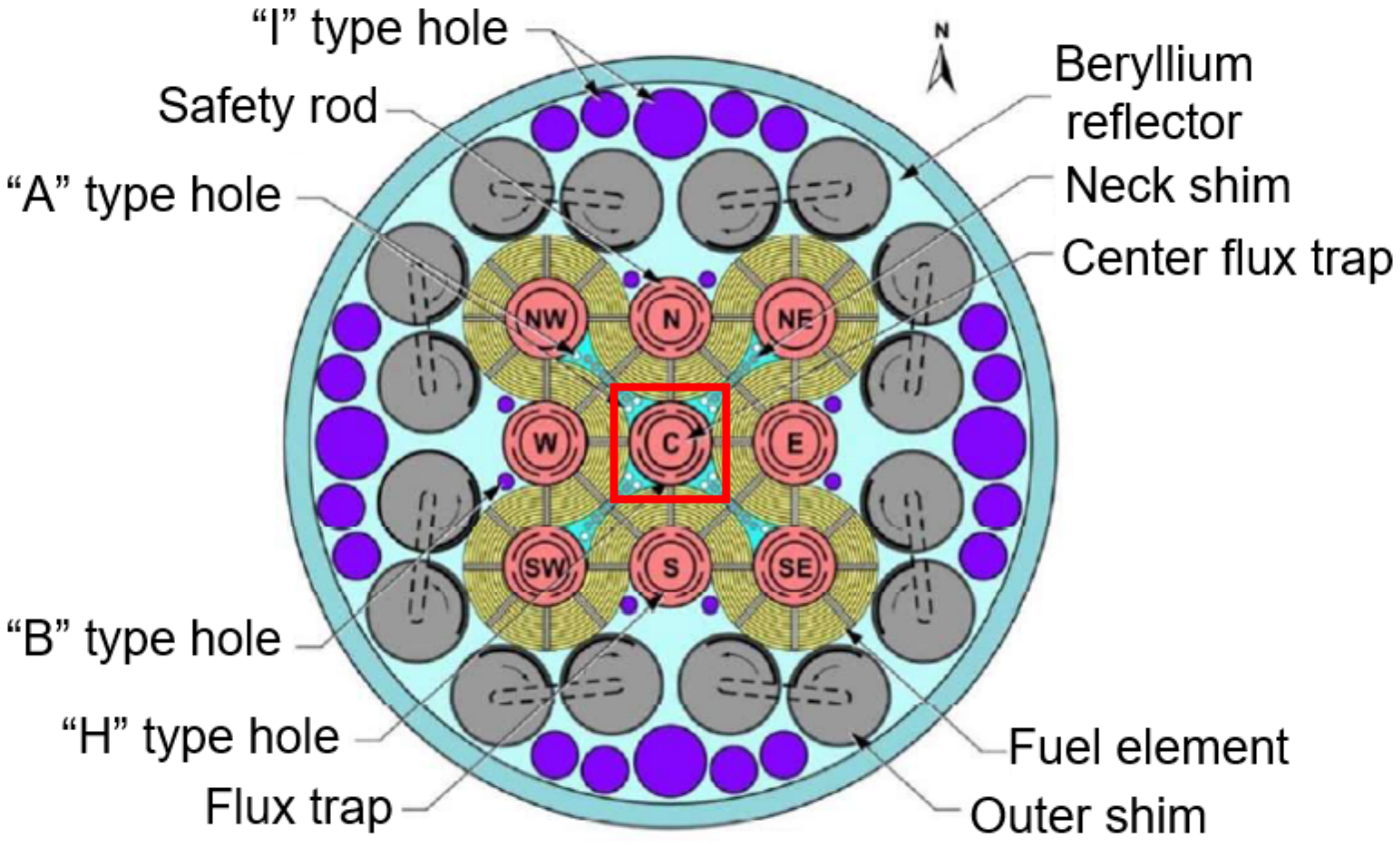
Element	Mo	C	Nb	Co	Cr	Fe	Mn	Ni	Ti
wt%	2.17	0.027	0.2	0.016	20.76	58.88	4.59	12.82	0.001

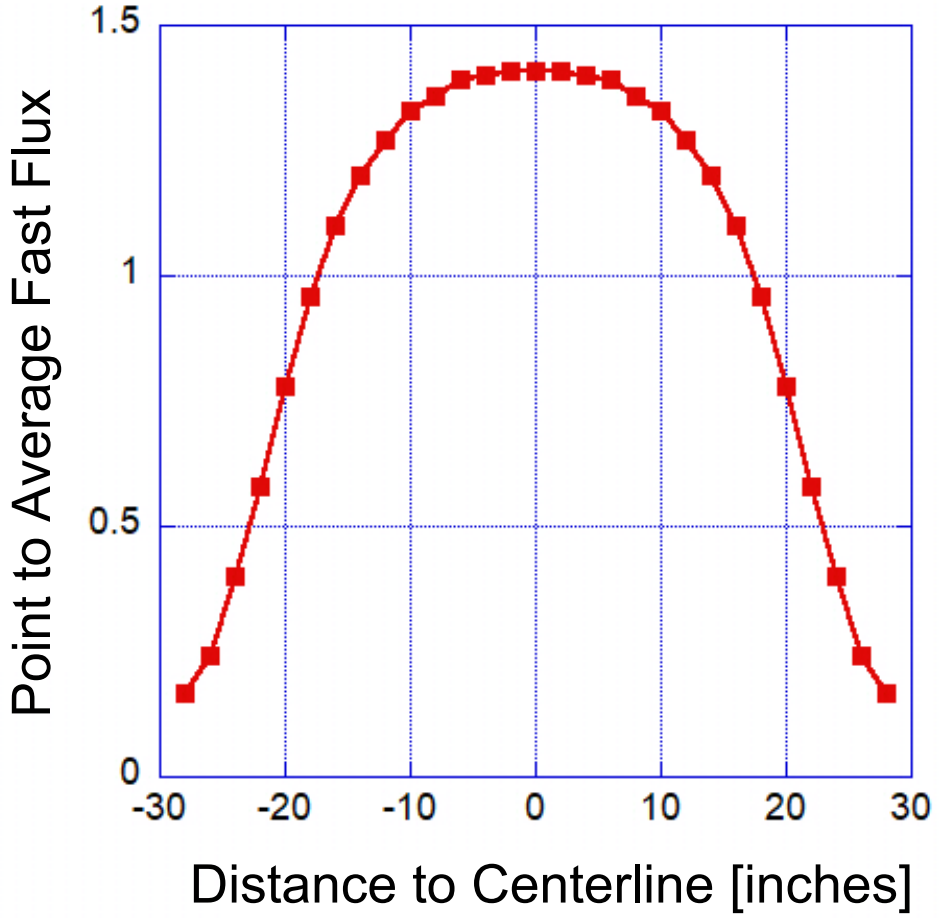




ATR Testing Location and Normal Operating Flux

ATR CFT nominal fast flux: 9.7 x 10^{13} n/cm^2-s





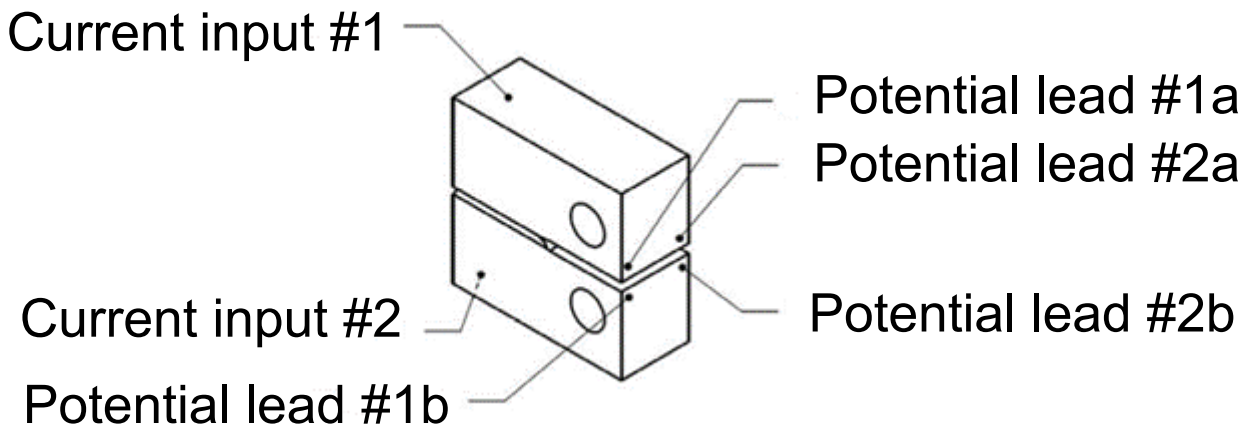
Measured Parameters for ATR Irradiation

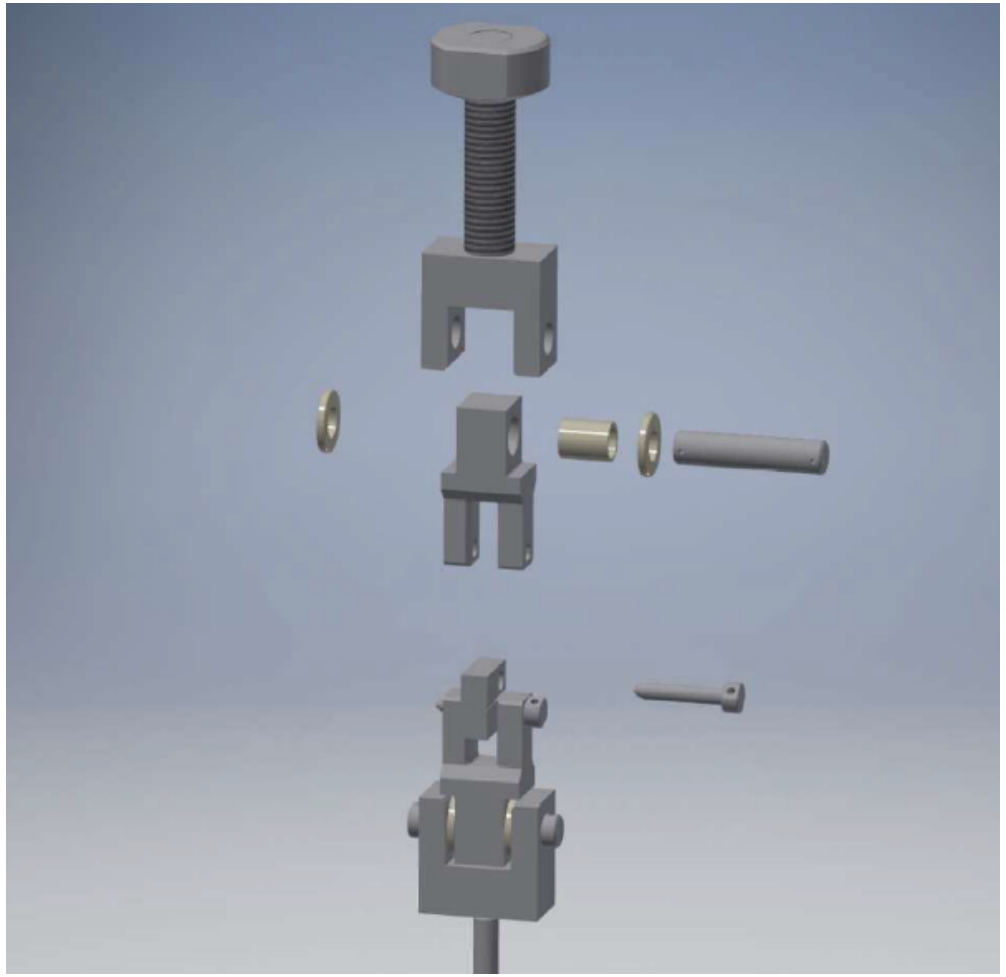
- MCNP analysis used to perform estimate of accumulated fluence
- ABAQUS model compared to packages of melt wires to estimate sample temp during irradiation
- Multiple 0.4T-CT samples of each alloy were tested from the ~0.3 and ~1.4 dpa irradiations

Specimen ID	Alloy	Fast Fluence (x10^{20})	dpa	Min Temp [°C]	Max Temp [°C]
10A0002 A10	X-750	1.93	0.309	349	359
10A0002 A08	X-750	1.89	0.302	329	338
10A0001 B03	XM-19	1.93	0.294	349	359
10A0001 B02	XM-19	1.89	0.291	350	369
10A0002 B03	X-750	8.658	1.441	287/257	295/259
10A0002 B09	X-750	9.704	1.542	335/265	347/268
10A0001 D02	XM-19	9.487	1.443	329/262	341/265
10A0001 B07	XM-19	8.658	1.320	287/257	295/259

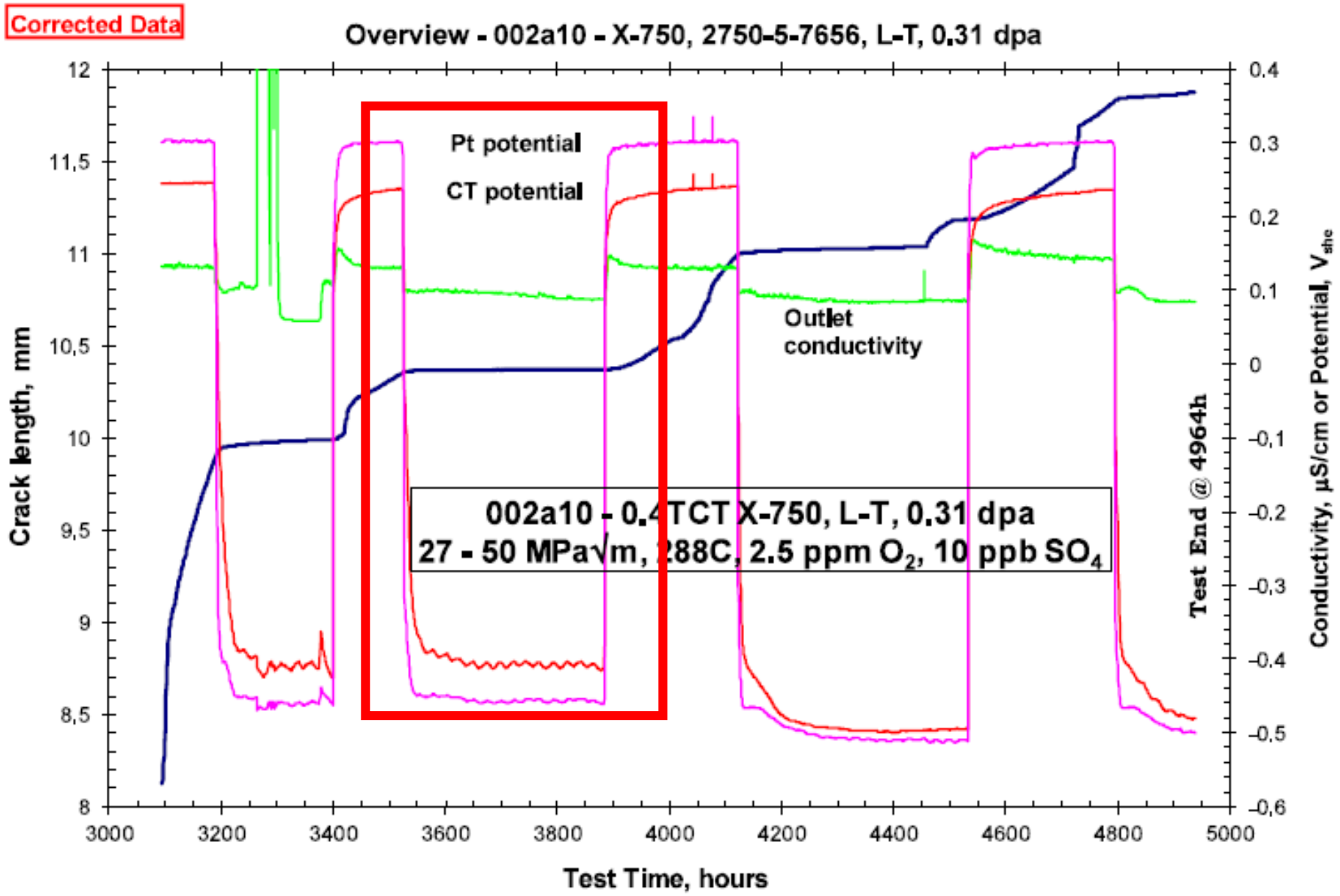
CGR Testing of Irradiated Samples using DCPD

- 3 A direct current used for DCPD crack monitoring
- Water in autoclave during experiment kept at 288 °C, 1500 psig
- 10 ppb sulfate (as H_2SO_4) added to enhance reproducibility and allow for comparison with experiments using non-irradiated samples
- NWC: 2.5 ppm dissolved oxygen
- HWC: 60-90 ppb dissolved hydrogen

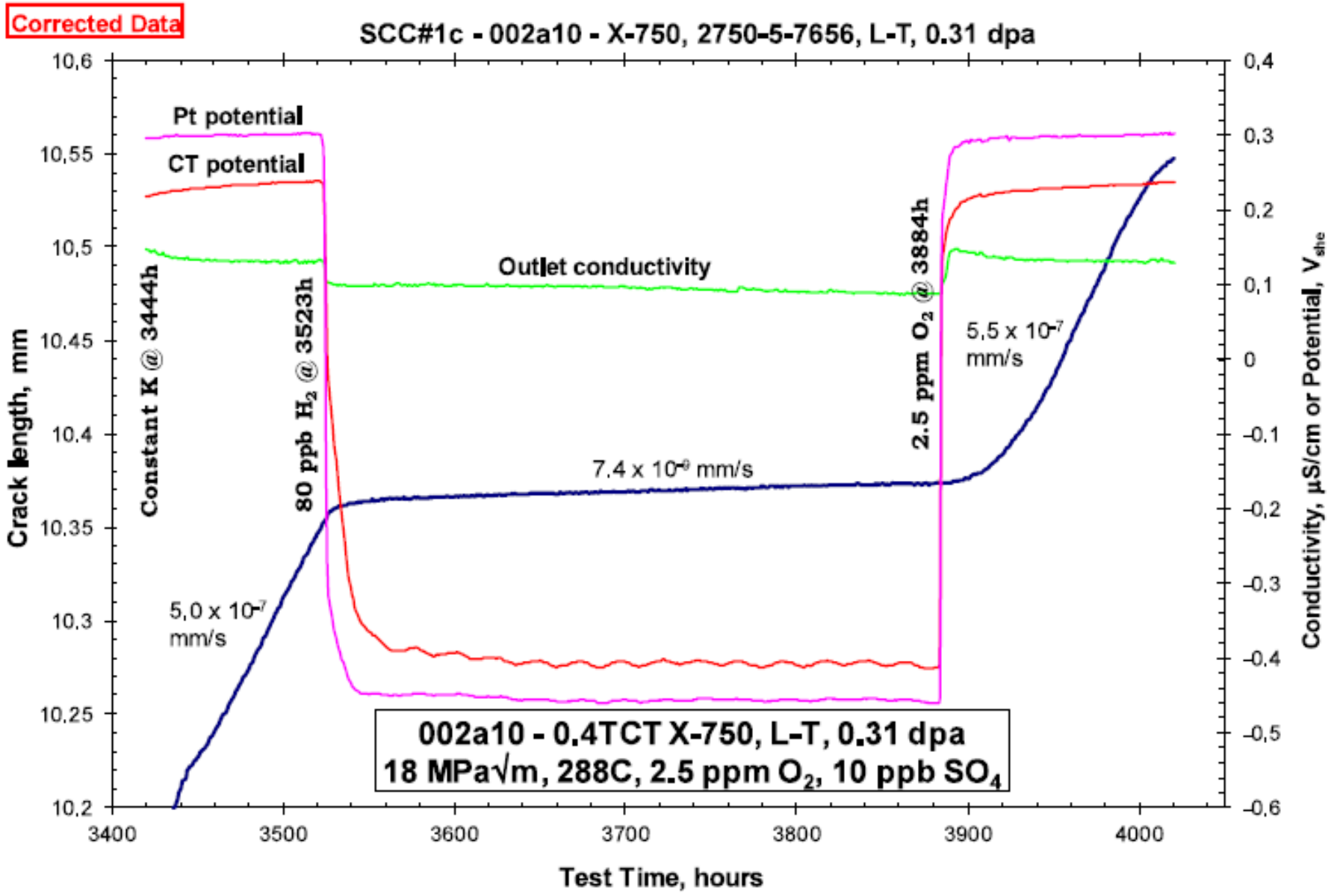




X-750 ~0.3 dpa CGR (02A10) – Overview of CGR Test

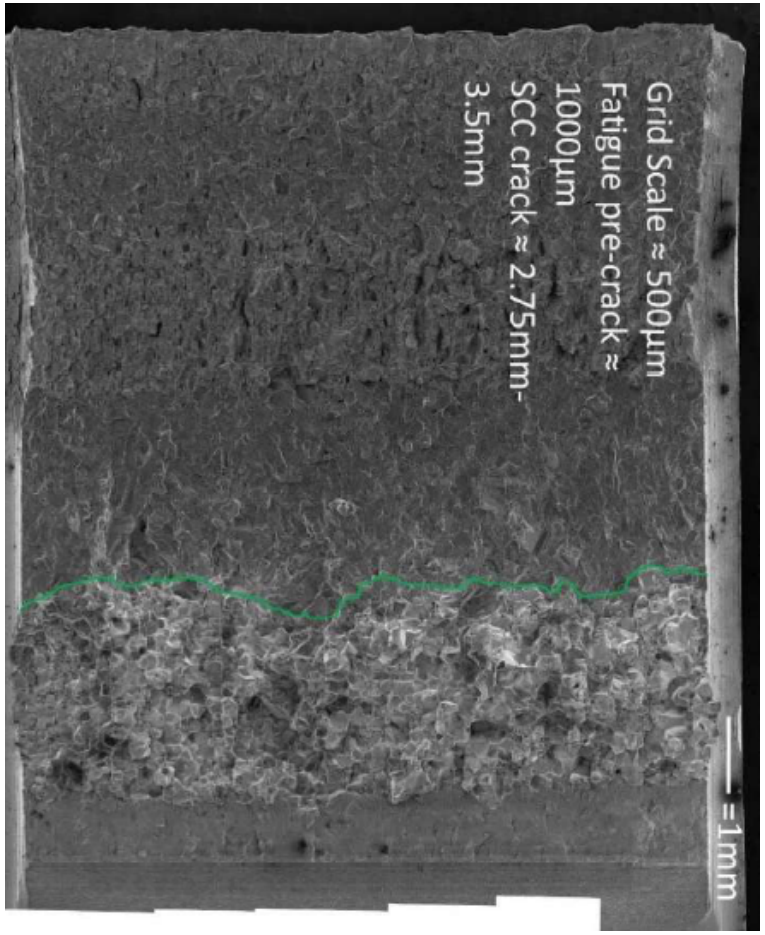


X-750 ~0.3 dpa CGR (02A10) – Selected Evaluation Step



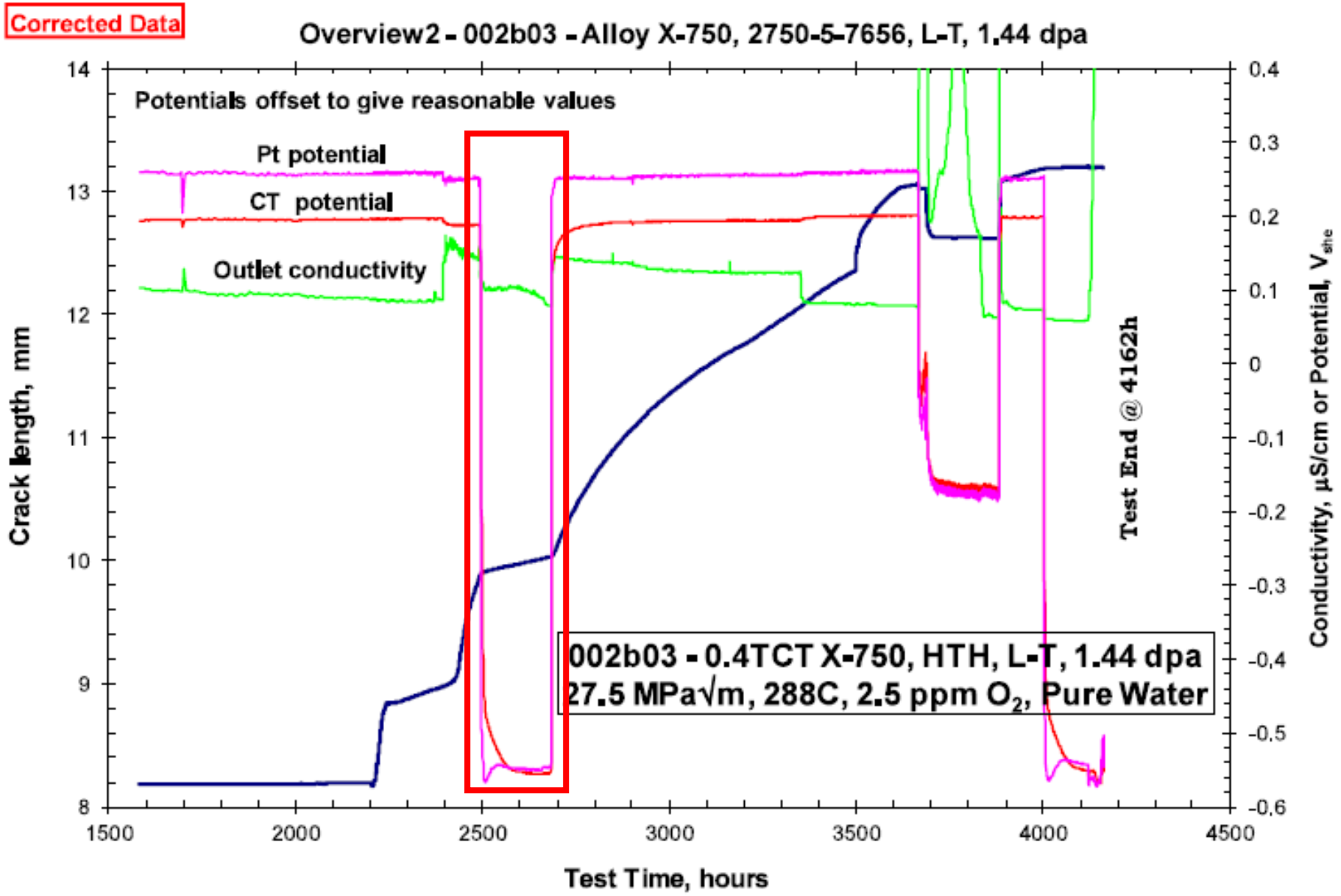
X-750 ~0.3 dpa CGR (02A10) - Results

Test Hours	K (MPa√m)	Chemistry	Sulfate	Outlet Cond (µS/cm)	Time Increment (hr)	Growth Increment (mm)	Average CGR (mm/s)
3146	28	NWC	10	0.131	41	0.394	2.60E-06
3187	29	HWC	10	0.062	212	0.112	3.60E-08
3399	29	NWC	10	0.15	20	0.032	1.00E-06
3444	18	NWC	10	0.13	79	0.130	5.00E-07
3523	18	HWC	10	0.095	361	0.023	7.40E-09
3884	18	NWC	10	0.13	137	0.456	5.50E-07
4077	30	NWC	10	0.13	43	0.161	1.10E-06
4120	30	HWC	10	0.08	335	0.048	1.90E-08
4532	30	NWC	10	0.15	188	0.278	5.80E-07
4730	49	NWC	10	0.145	62	0.132	6.50E-07
4792	50	HWC	10	0.085	172	0.041	6.50E-08

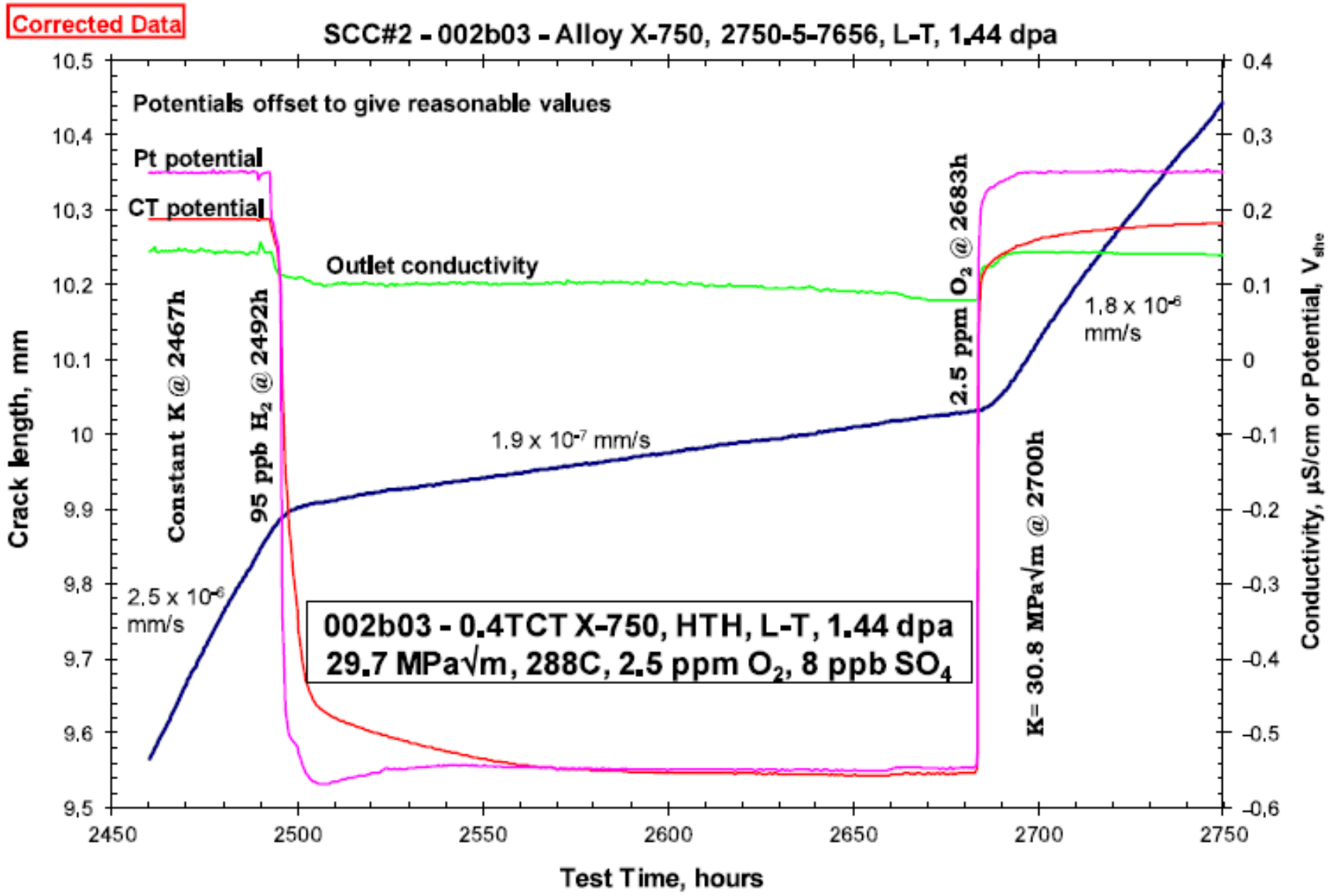


rows highlighted in blue denote measurements which were taken at a high degree of confidence

X-750 ~1.4 dpa CGR (02B03) – Overview of CGR Test

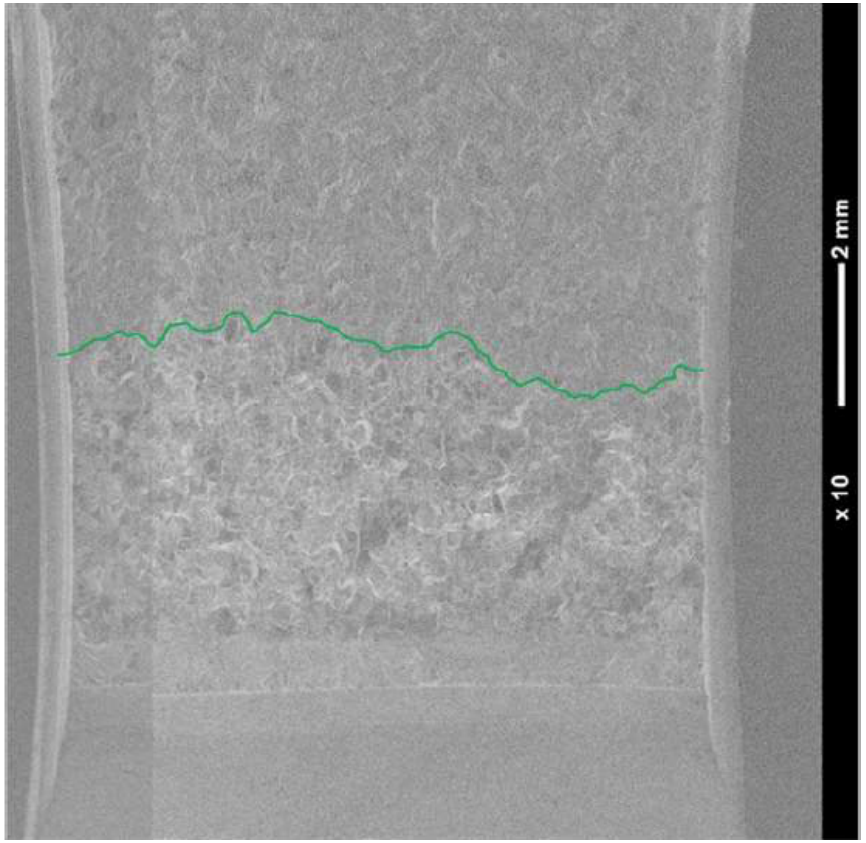


X-750 ~1.4 dpa CGR (02B03) – Selected Evaluation Step



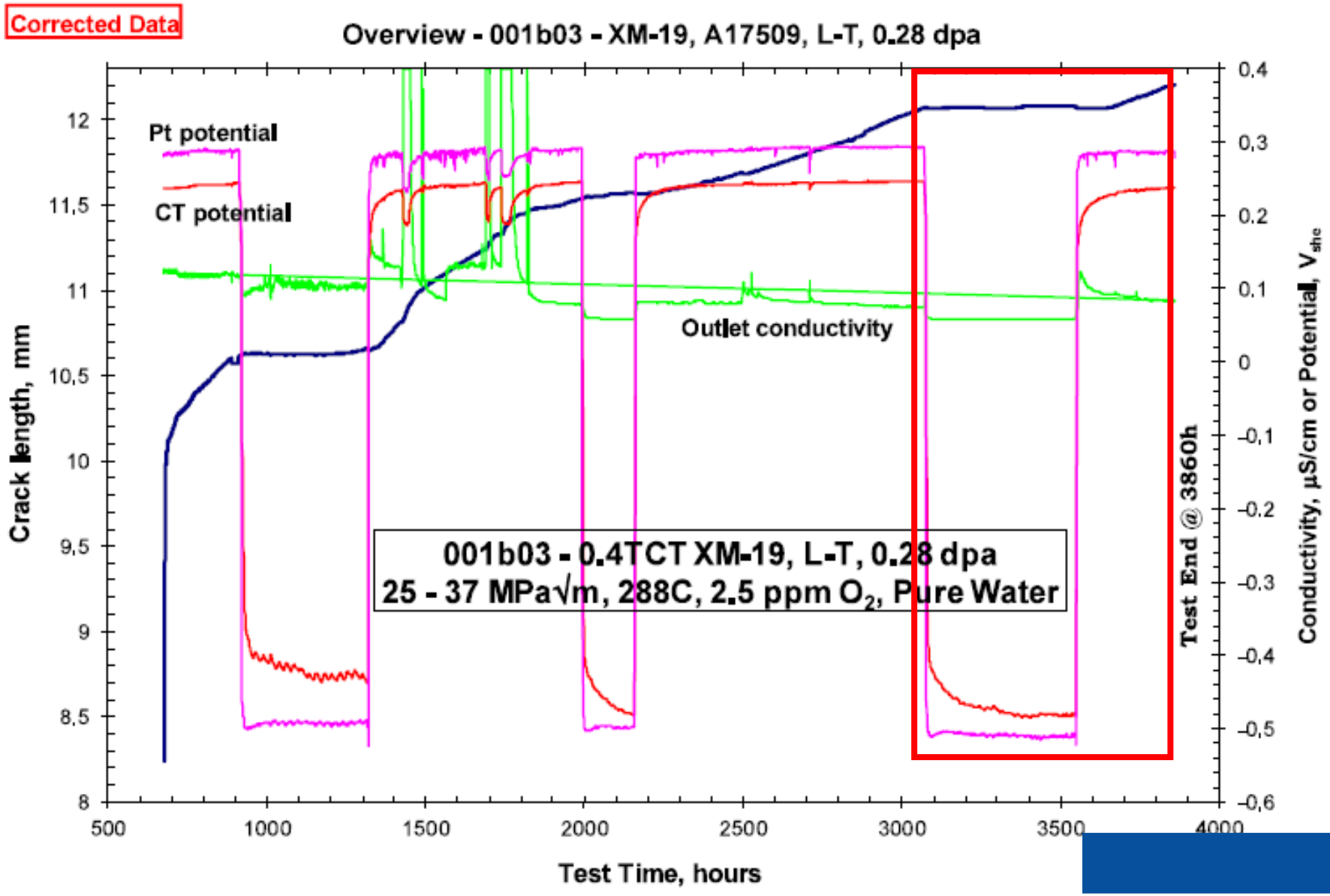
X-750 ~1.4 dpa CGR (02B03) – Results

Test Hours	K (MPa√m)	Chemistry	Sulfate	Outlet Cond (µS/cm)	Time Increment (hr)	Growth Increment (mm)	Average CGR (mm/s)
2467	29	NWC	8	0.148	25	0.232	2.50E-06
2492	30	HWC	8	0.1	191	0.160	1.90E-07
2683	31	NWC	8	0.141	70	0.428	1.80E-06
3174	22	NWC	8	0.123	177	0.346	5.20E-07
3351	23	NWC	0	0.082	146	0.291	4.50E-07
3887	24	NWC	0	0.073	115	0.104	2.60E-07
4002	26	HWC	0	0.06	151	0.013	3.60E-08

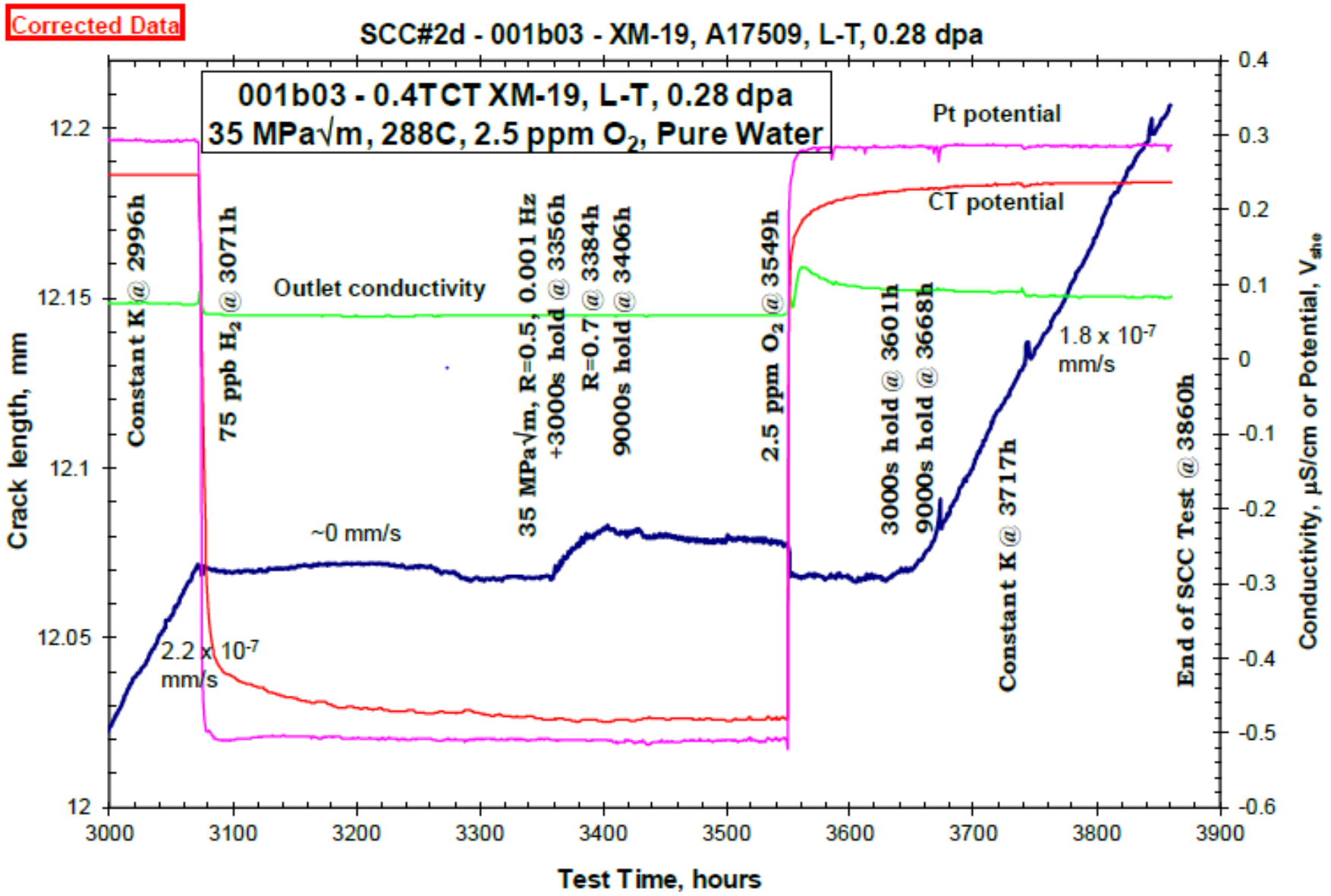


rows highlighted in blue denote measurements which were taken at a high degree of confidence

XM-19 ~0.3 dpa CGR (01B03) – Overview of CGR Test

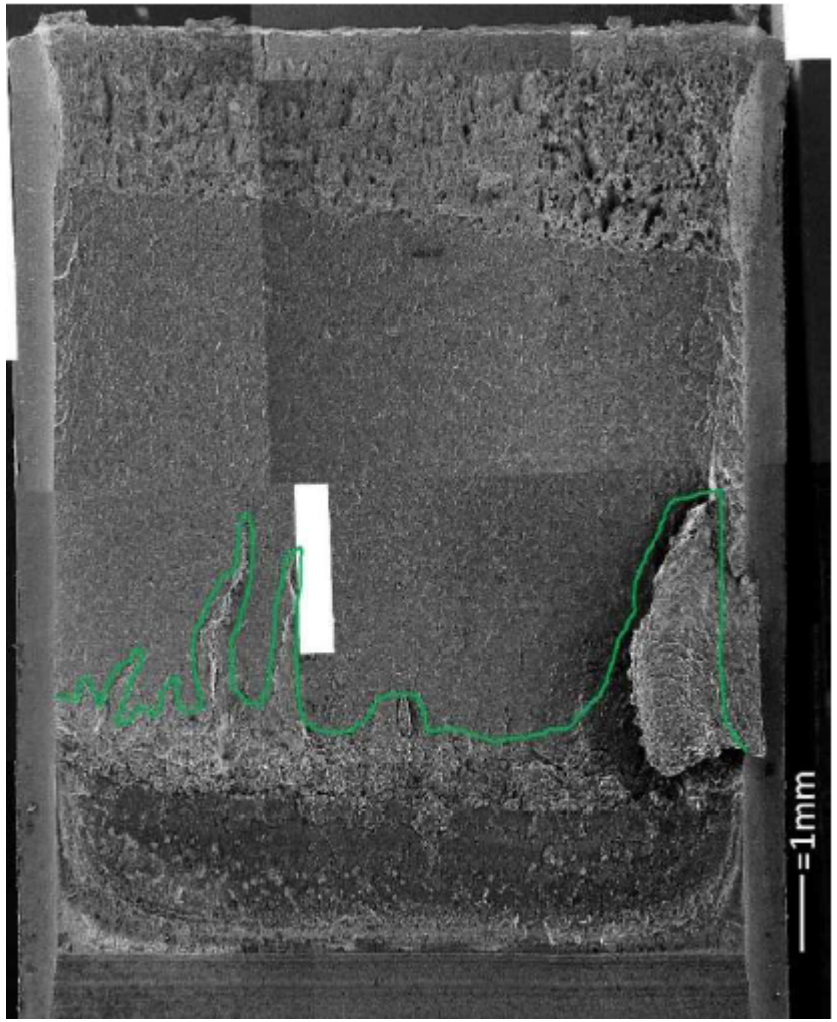


XM-19 ~0.3 dpa CGR (01B03) – Selected Evaluation Step



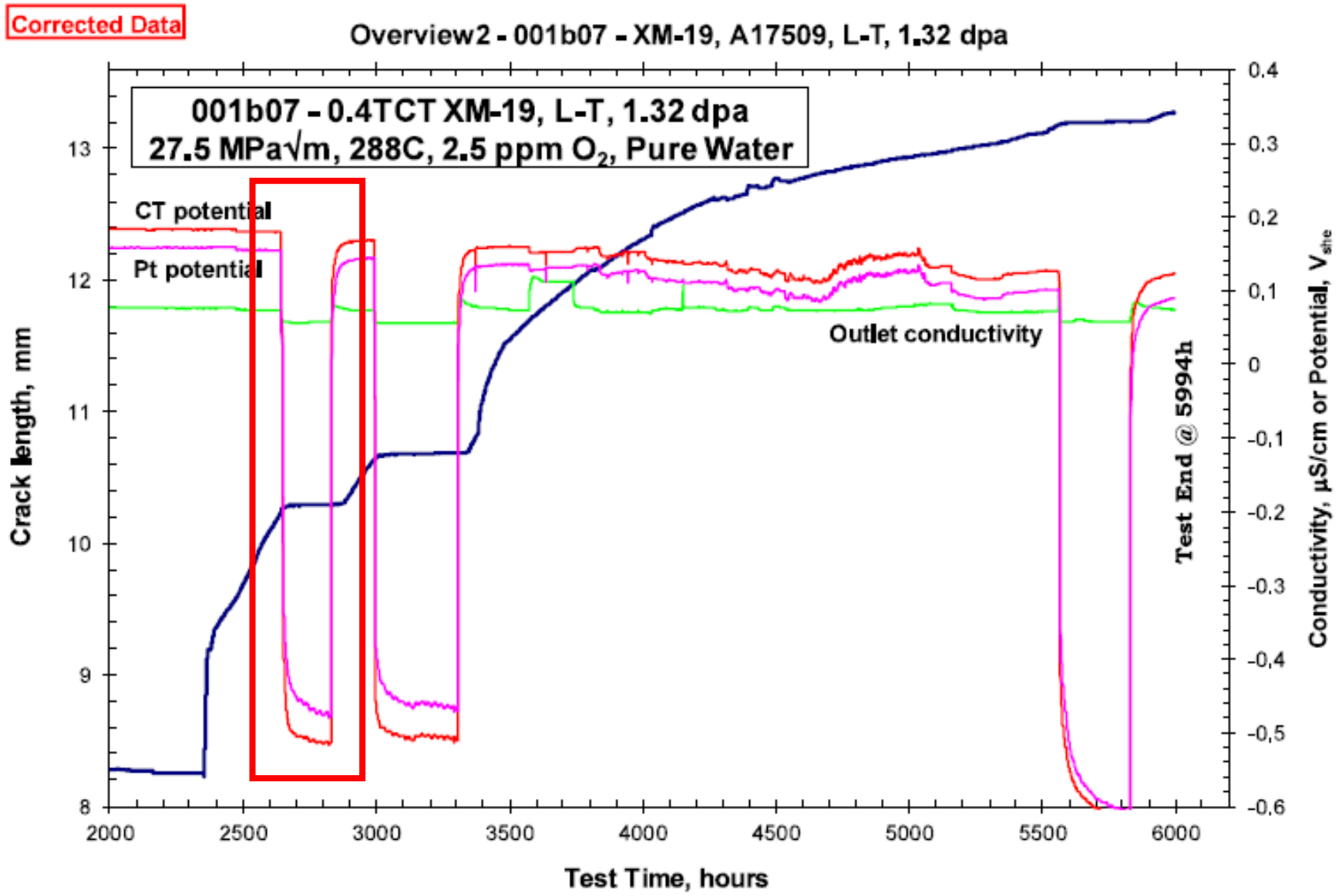
XM-19 ~0.3 dpa CGR (01B03) - Results

Test Hours	K (MPa√m)	Chemistry	Sulfate	Outlet Cond (µS/cm)	Time Increment (hr)	Growth Increment (mm)	Average CGR (mm/s)
1537	33	NWC	0	0.087	24	0.028	3.20E-07
1561	33	NWC	10	0.129	261	0.362	3.20E-07
1844	33	NWC	0	0.08	148	0.059	1.60E-07
1992	33	HWC	0	0.059	69	0.015	2.00E-08
2540	35	NWC	0	0.081	314	0.193	1.80E-07
2996	35	NWC	0	0.075	79	0.049	2.20E-07
3076	35	HWC	0	0.059	280	0.000	1.00E-09
3717	35	NWC	0	0.083	143	0.092	1.80E-07

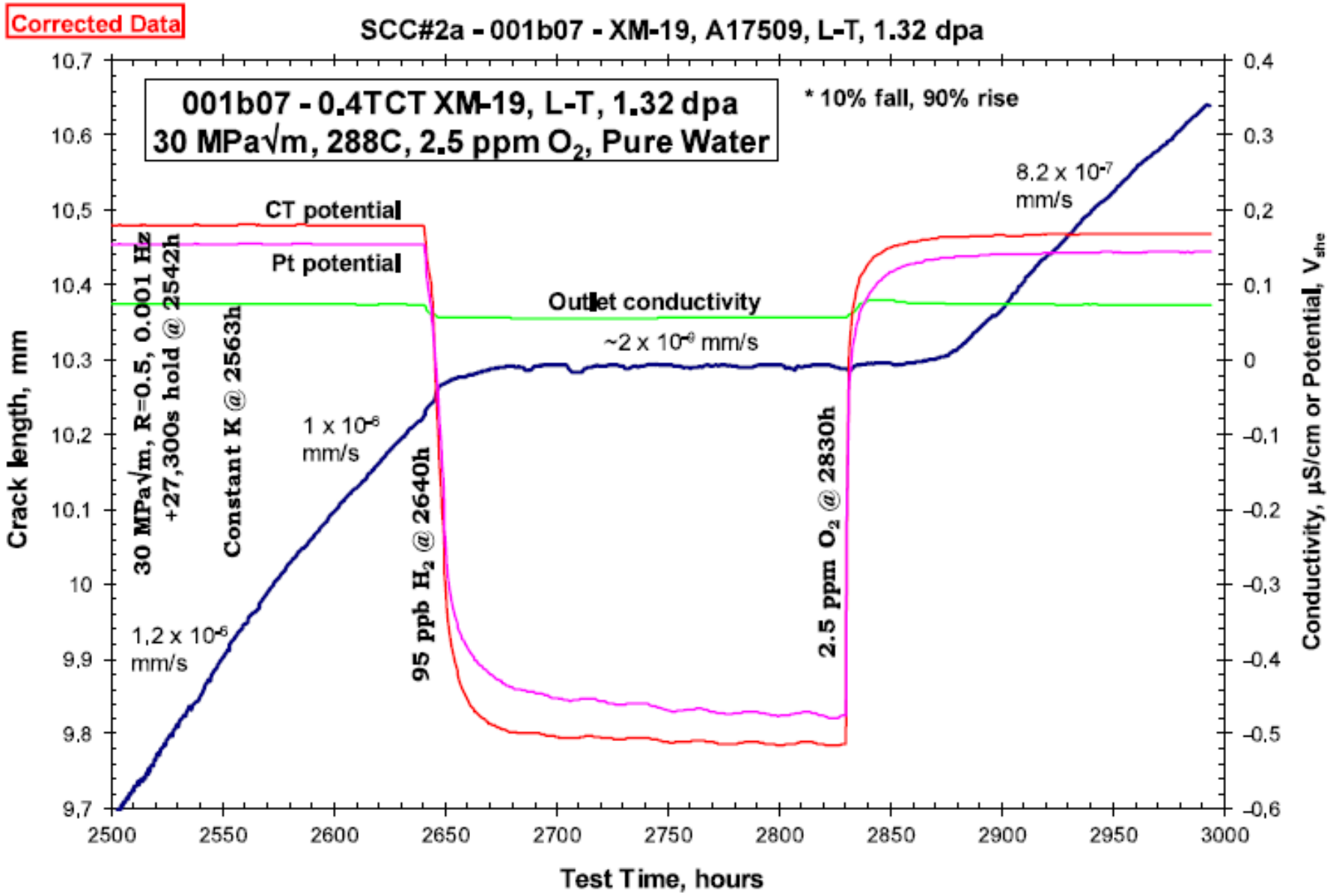


rows highlighted in blue denote measurements which were taken at a high degree of confidence

XM-19 ~1.5 dpa CGR (01B07) – Overview of CGR Test

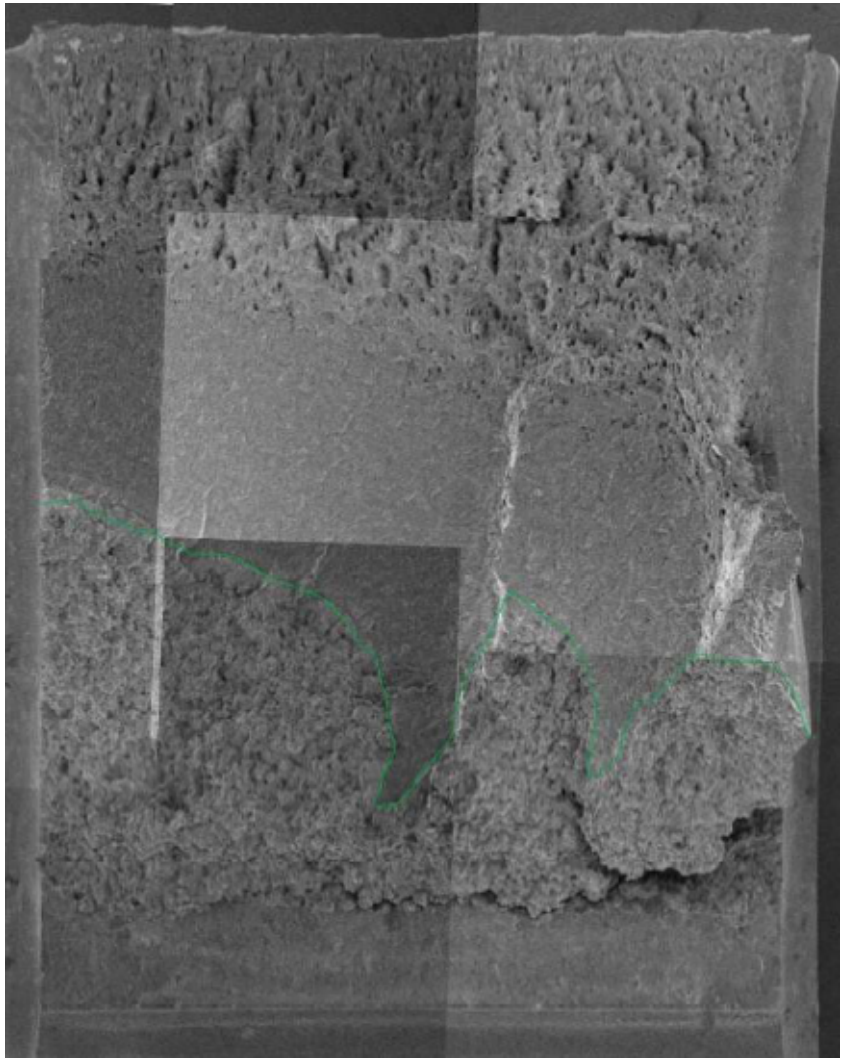


XM-19 ~1.4 dpa CGR (01B07) – Selected Evaluation Step



XM-19 ~1.4 dpa CGR (01B07) – Results

Test Hours	K (MPa√m)	Chemistry	Sulfate	Outlet Cond (µS/cm)	Time Increment (hr)	Growth Increment (mm)	Average CGR (mm/s)
2563	30	NWC	0	0.074	77	0.263	1.00E-06
2640	30	HWC	0	0.058	190	0.063	2.00E-09
2830	32	NWC	0	0.073	164	0.355	8.20E-07
2994	33	HWC	0	0.056	312	0.047	1.60E-08
3306	34	NWC	0	0.078	76	0.150	1.00E-06
3480	36	NWC	0	0.074	92	0.176	5.40E-07
3572	36	NWC	8	0.113	243	0.389	5.40E-07
3815	36	NWC	0	0.07	164	0.204	5.40E-07
5213	23	NWC	0	0.072	350	0.176	2.00E-07
5563	23	HWC	0	0.057	265	0.024	3.00E-09



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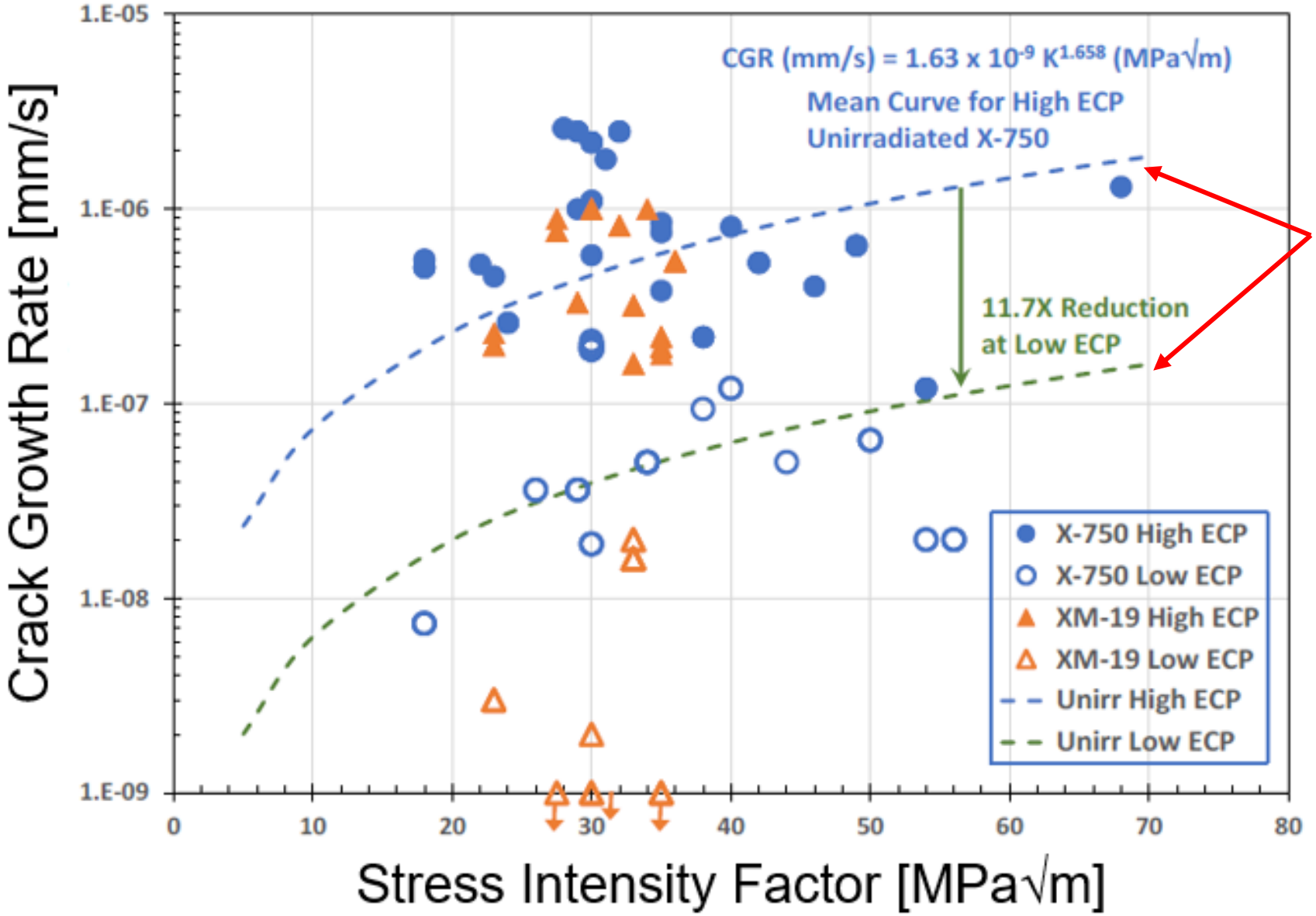
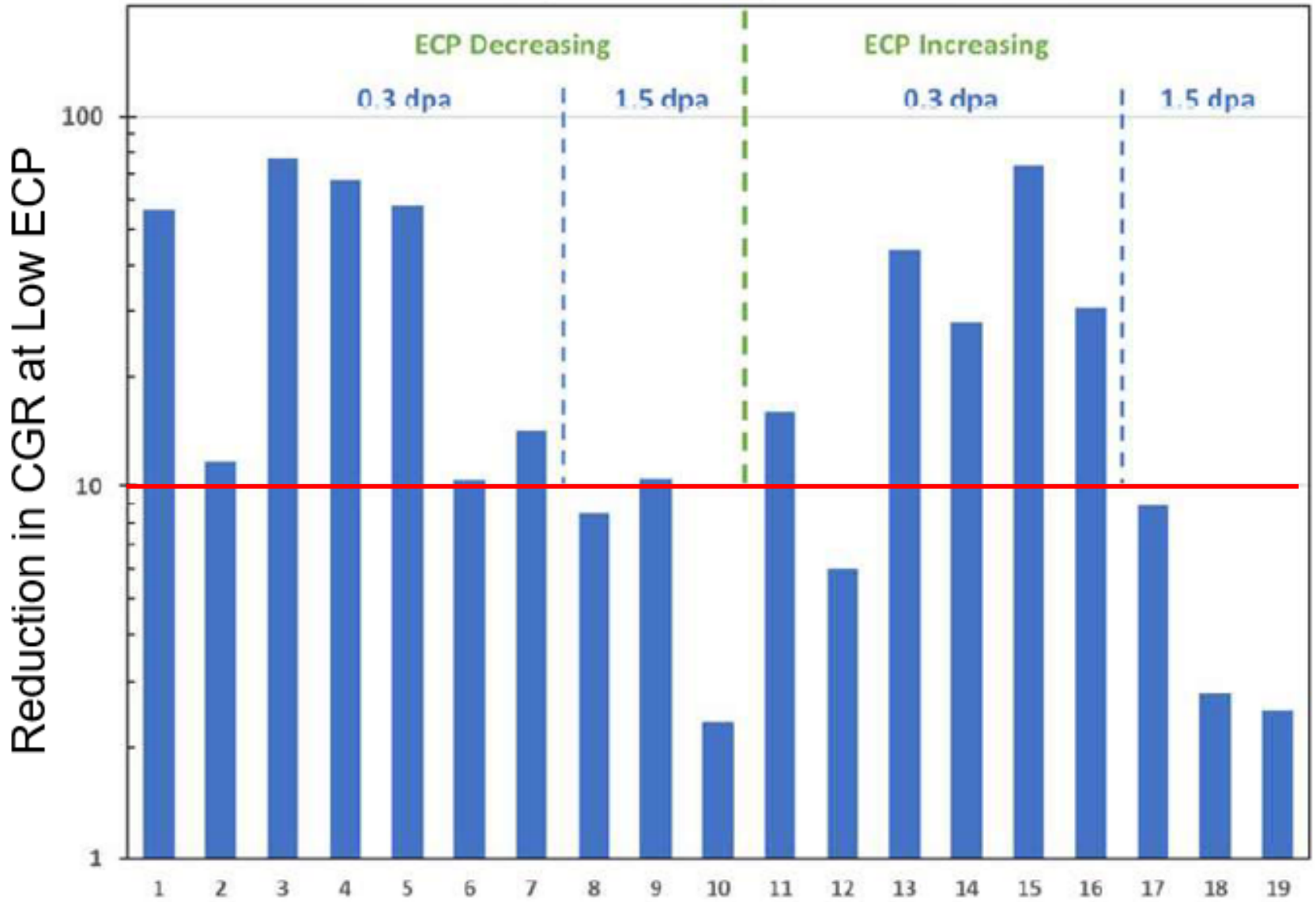
Compiled CGR Data for Neutron Irradiated X-750 and XM-19



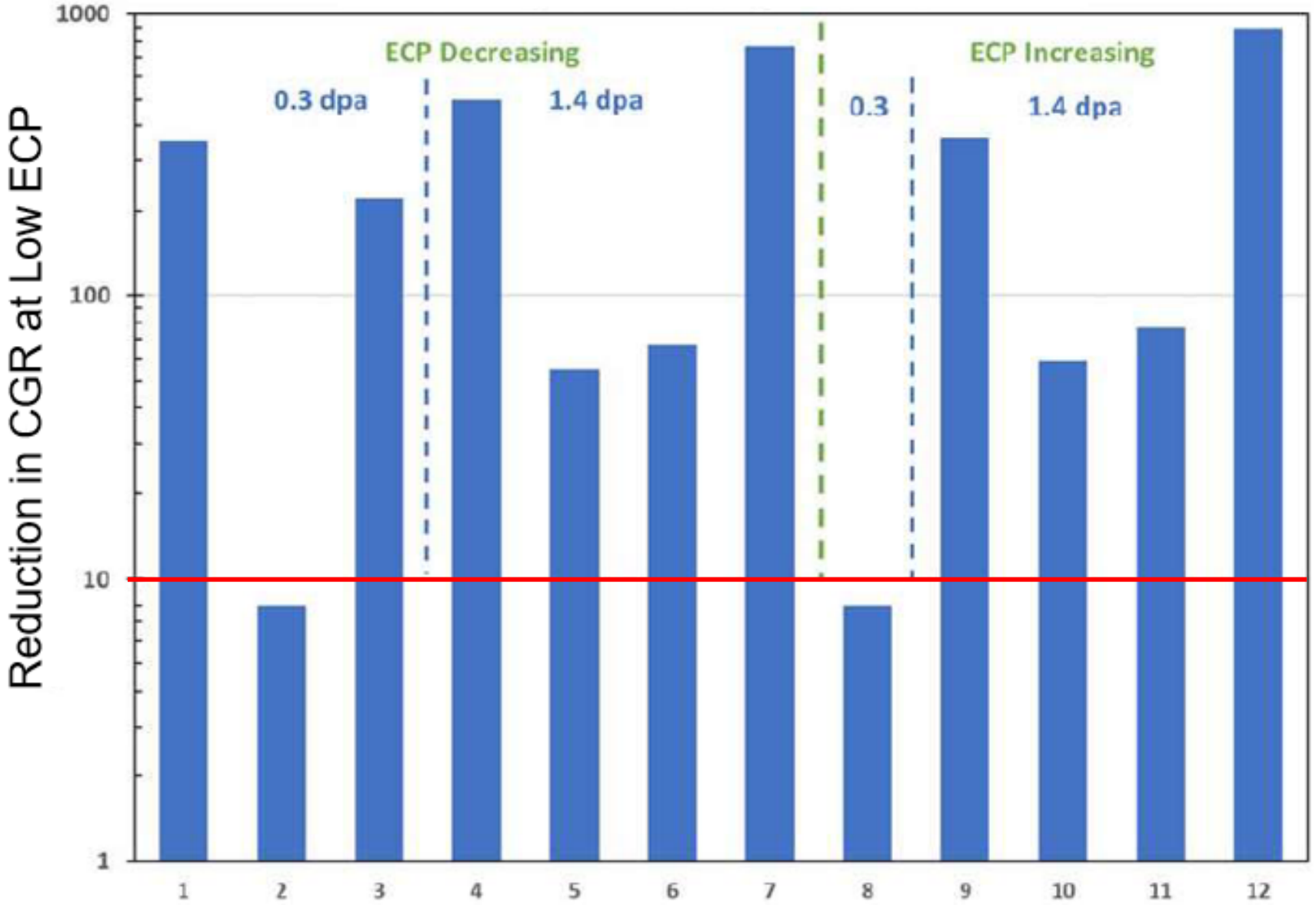
Dashed lines represent curves generated from non-irradiated data

Effect of Low/High ECP on X-750 CGR



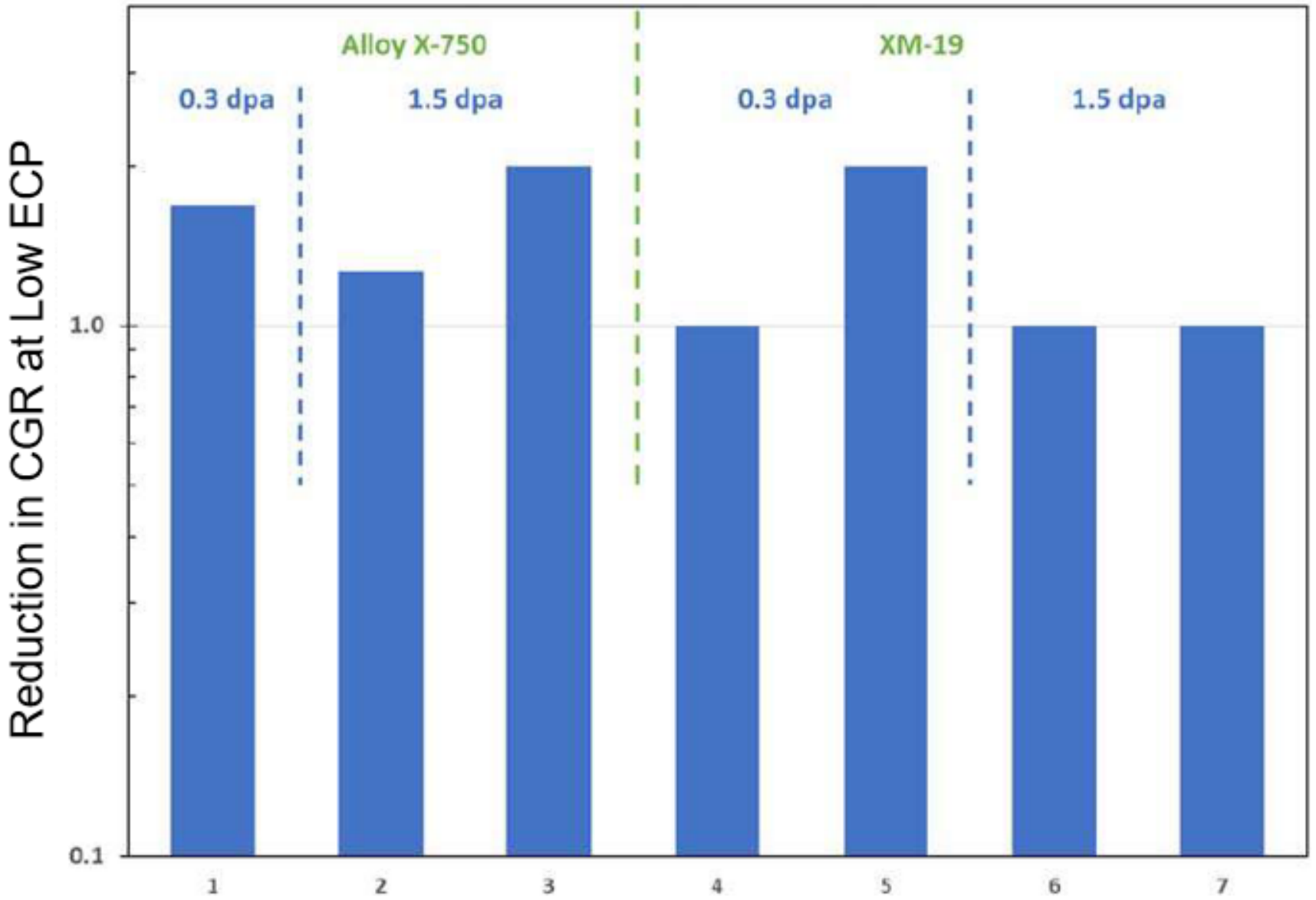
- Data represents results from both ~0.3 dpa and ~1.4 dpa samples
- Average CGR reduction at low ECP = 28x

Effect of Low/High ECP on XM-19 CGR



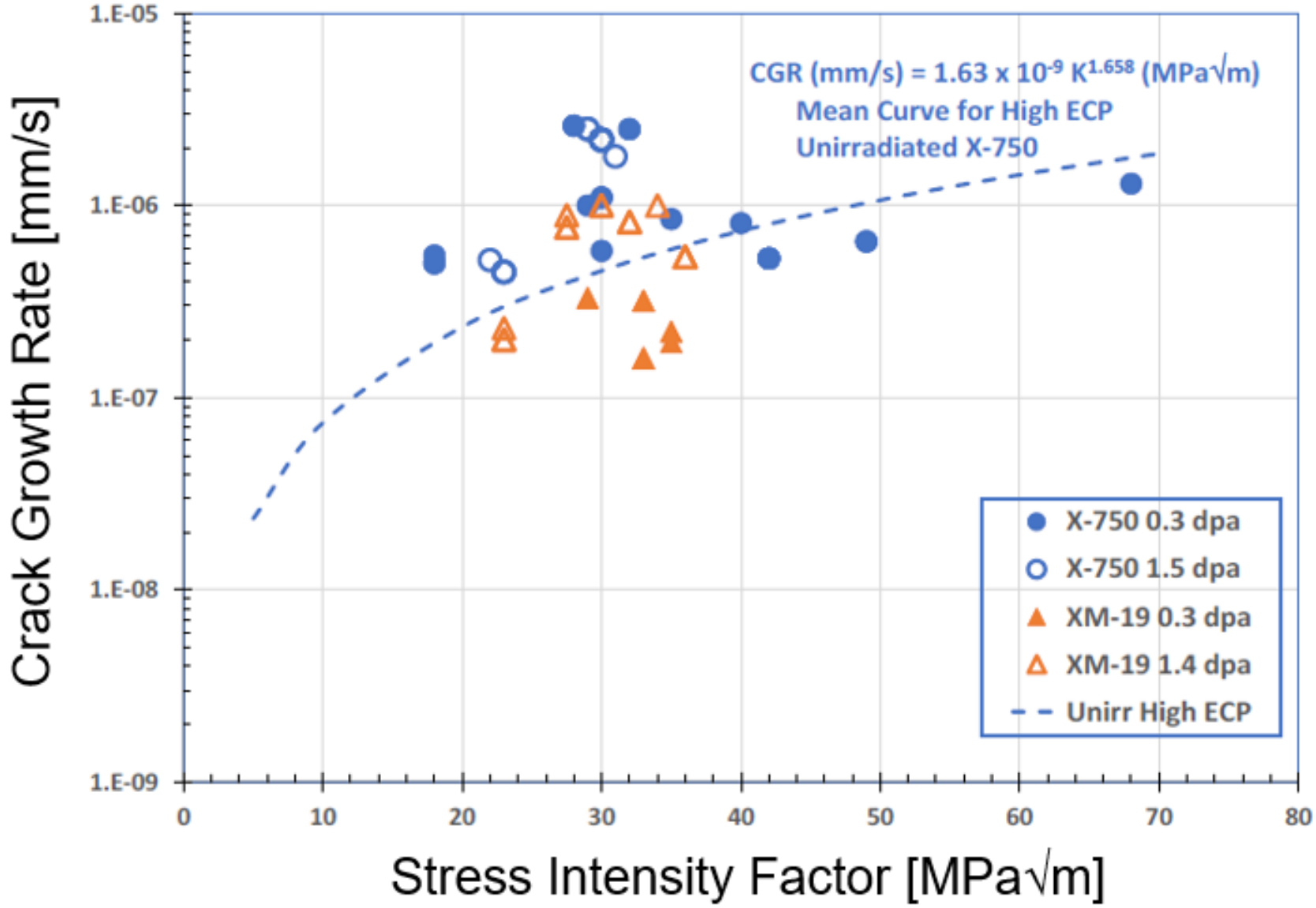
- Data represents results from both ~0.3 dpa and ~1.4 dpa samples
- Average CGR Reduction at Low ECP = 278x

Effects of Sulfate Additions on X-750 and XM-19 CGR



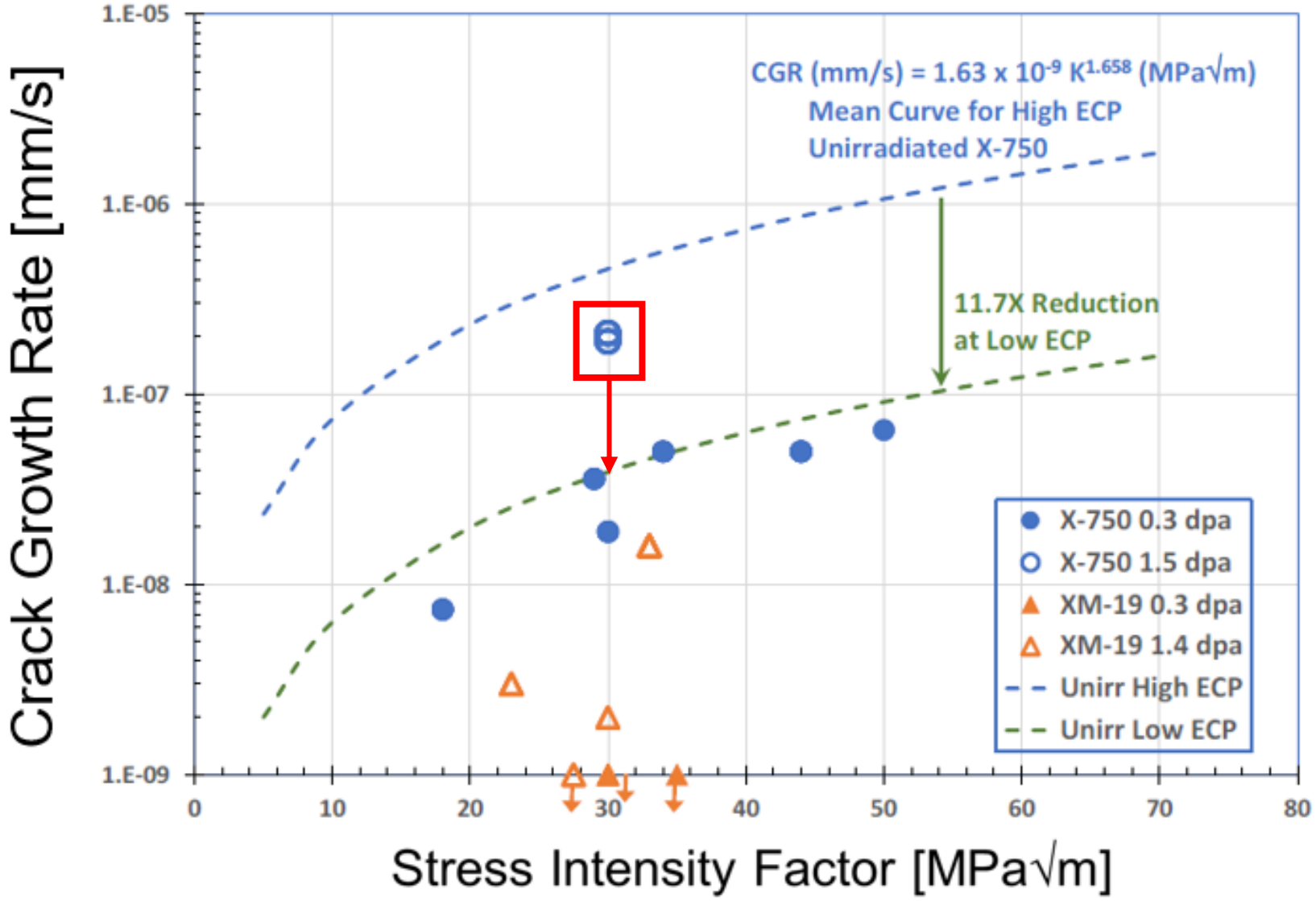
- Data represents results from both ~0.3 dpa and ~1.4 dpa samples
- Average reduction in CGR due to changing sulfate additions = 1.4x

Effect of Dose on CGR in Neutron Irradiated X-750 and XM-19 (High ECP)



Data shows higher quality, high ECP data collected at INL

Effect of Dose on CGR in Neutron Irradiated X-750 and XM-19 (Low ECP)



Conclusion

- First of its kind experiment for the civilian sector performed in the ATR CFT
- Significant changes in CGR were observed for neutron irradiated X-750 and XM-19 after switching between NWC and HWC environments (28x for X-750, 278x for XM-19)
- Slight effect (~1.4x) on CGR observed after changing between 10 ppb sulfate and pure water
- Overall CGR of irradiated samples was similar to non-irradiated CGR data, supplying evidence that the CGR of these alloys show limited sensitivity to dose
- Effect of dose on the CGR in neutron irradiated X-750 and XM-19 was only distinct in the low ECP environment, however the very low growth rates observed in HWC for these alloys reduces the confidence of this conclusion