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PA-MS-C-0257

**PWSCC Crack Initiation Testing of Farley
Unit 2 Alloy 600 CRDM Penetrations**

Project Authorization Update

Rich Jacko – Westinghouse Churchill

Technical Lead

WEC CCOE/MCOE Group

Date: June 2014

Background

- EPRI and PWROG have approved programs to study the effects of zinc addition on PWSCC
 - Ultimate Industry Goal – NRC acceptance of Zinc as a chemical mitigation method to support inspection relief requests.
- PWROG PA-MS-C-0257 “PWSCC Crack Initiation Testing of Farley Unit 2 Alloy 600 CRDM Material” approved February 2006
 - Verify the enhanced PWSCC resistance of CRDM Heat M3935 at Farley is due to zinc additions.
 - Exposure of Alloy 600, Alloy 690, 82/182, and 52/152 materials to demonstrate that the benefits of soluble zinc extend to other primary side Alloy 600/Alloy 690 components and their associated welds.
 - Develop technical strategies to support utility requests to the NRC for inspection interval relief for Alloy 600 and Alloy 690 wetted surfaces.

Background

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Farley 2: Pilot Plant for Zinc Addition – significantly less PWSCC Observed

Plant name	# of nozzles heat no. M3935	% in industry heat no. M3935	# inspected by UT	# required repair	% of M3935 in RV head with defect
Oconee 3	68	49%	68	14	20%
Davis Besse	5	4%	5	3	60%
ANO 1	1	<1%	1	1	100%
Beaver Valley 1	4	3%	4	4	100%
Farley 2	61	44%	61	0	0%
Total	139		139	22	
%			100%	16%	

Farley 2: Pilot Plant for Zinc Addition

- Laboratory and test reactor experiments indicated reduced general corrosion and PWSCC mitigation benefits of zinc addition
- EPRI sponsored demonstration plant
- Zinc injection began
June 12, 1994

Reactor Vessel head EDY = 9.2 at start

Purpose

- PWSCC Initiation test have been performed:
 - In baseline, simulated primary water
 - In primary water with ~ 8 ppb dissolved zinc (experimental range 2 – 13 ppb zinc)
 - Some specimens pre-treated with zinc exposure in an unstressed condition prior to PWSCC testing
 - Purpose: Determine how zinc and prior zinc exposure affects PWSCC initiation and relevant factor of improvement associated with zinc

Benefits

- The output of this program is expected to factor into the overall XLPR framework to provide some credit for chemical mitigation of PWSCC for both:
 - Alloy 600 and Alloy 82/182 welds
 - Alloy 690 and Alloy 52M/152 welds

Work Scope

- Task 1 – Task 3 are complete
- Task 3 involved > 1 year baseline testing of these materials with the zinc layer removed
- Task 4 – Multi-year PWSCC Initiation Testing with Zinc additions and various starting zinc exposures
- Task 4 – Exposures completed Fall 2013 with preliminary inspections
- Final SEM inspections performed
- Detailed measurements of chemical effects associated with Zinc addition on the oxide films

Project Status

- Hot operation June 2011 to October 2013
- Test temperature 689°F (365°C) for thermal acceleration
- Accumulated ~18,064 hrs of at-temperature operation (>550F) and final Exposure 55.6 EDY at Inspection 9
- Recall EDY = effective time at 600°F
- Optical examinations complete; final load checked and all specimens were unloaded with minimal relaxation
- No addition PWSCC experienced over the last period
- Final SEM exams complete
- Limited cross-sectional metallography underway

Long term exposure

- Recall Task 4 coupons exposed for 55.6 EDY
- Specimens that were also exposed in Task 3 or other W programs have longer total exposures as indicated below (63.8 to 80.2 EDY)

period / inspection	target cum. Hours	actual cum. hours	target EDY	actual EDY w zinc	task 3 + 4 total EDY	A82/182 total EDY
1	1500	1768	4.7	4.8	29.4	13.0
2	3000	3184	9.3	9.1	33.7	17.3
3	4500	4967	14.0	14.7	39.3	22.9
4	6000	6165	18.7	18.4	43.0	26.6
5	8000	8327	24.9	25.1	49.7	33.3
6	10000	10676	31.1	32.5	57.1	40.7
7	12000	13369	37.3	40.9	65.5	49.1
8	15000	15708	46.7	48.3	72.9	56.5
9	18000	18064	56.0	55.6	80.2	63.8

Final PWSCC Initiation

Final Inspection	Alloy 600 Heat M3935			Alloy 600 weld metal		Newer Materials		
	Far#14 OD	Far#16 OD	DB#2 OD	Summer 182	Summer 82	690	52M	152
Task 3 results (control, 0 zinc) # PWSCC/Total at 24+ EDY	7/11	4/12	5/15	1/5	1/4	0/5	0/4	1/5
Starting Σ[Zinc]	at 55.6 EDY or 80.2 EDY			63.8 or 88.4 EDY		at 55.6 EDY or 80.2 EDY		
1800 - 2000 ppb-mo Zn	3-4 /11	0/9						
275 - 475 ppb-mo Zn	1/9	0/9	0/11	0/7	0/5	0/2	0/2	0/2
150- 350 ppb-mo Zn			1/6					
0 - 200 ppb-mo Zn			0/10			0/4	0/5	2/5
Subtotal Fresh	4/20	0/18	1/27	0/7	0/5	0/6	0/7	2/7
Subtotal	5-6 /65			0/12		2/20		
0 ppb-mo T3 Beams with no PWSCC & 24 0 - 200 ppb-mo Zn			3/9			0/1		0/1
275 ppb-mo Task 3 Beams with no PWSCC & 24 EDY 275 - 475 ppb-mo Zn	2/4	0-2 /8		1/3	2/3	0/2	0/2	0/2
Subtotal T3 + T4	2/4	0-2 /8	3/9	1/3	2/3	0/3	0/2	0/3
	5/21			3/6		0/8		
Total Number	6-7 /24	0-2 /26	4/36	1/10	2/7	0/9	0/9	2/10
Group Total	10/86			3/18		2/28		

Weibull PWSCC Initiation Analyses

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- Multiple Weibull analyses performed on various subsets of data
- Due to the general lack of PWSCC initiation observed with zinc exposure multiple Weibayes analyses often performed
- Task 3 results compared to identify the Factor-of-Improvement or FOI associated with zinc addition
- Results generally indicate a FOI of ~ 3+ times associated with zinc addition for Alloy 600 materials
- Improvements in the range of FOI of 2.0 to 2.5 were generally experienced for the Alloy 82/182 materials
- Some PWSCC initiation was seen in Alloy 152 materials

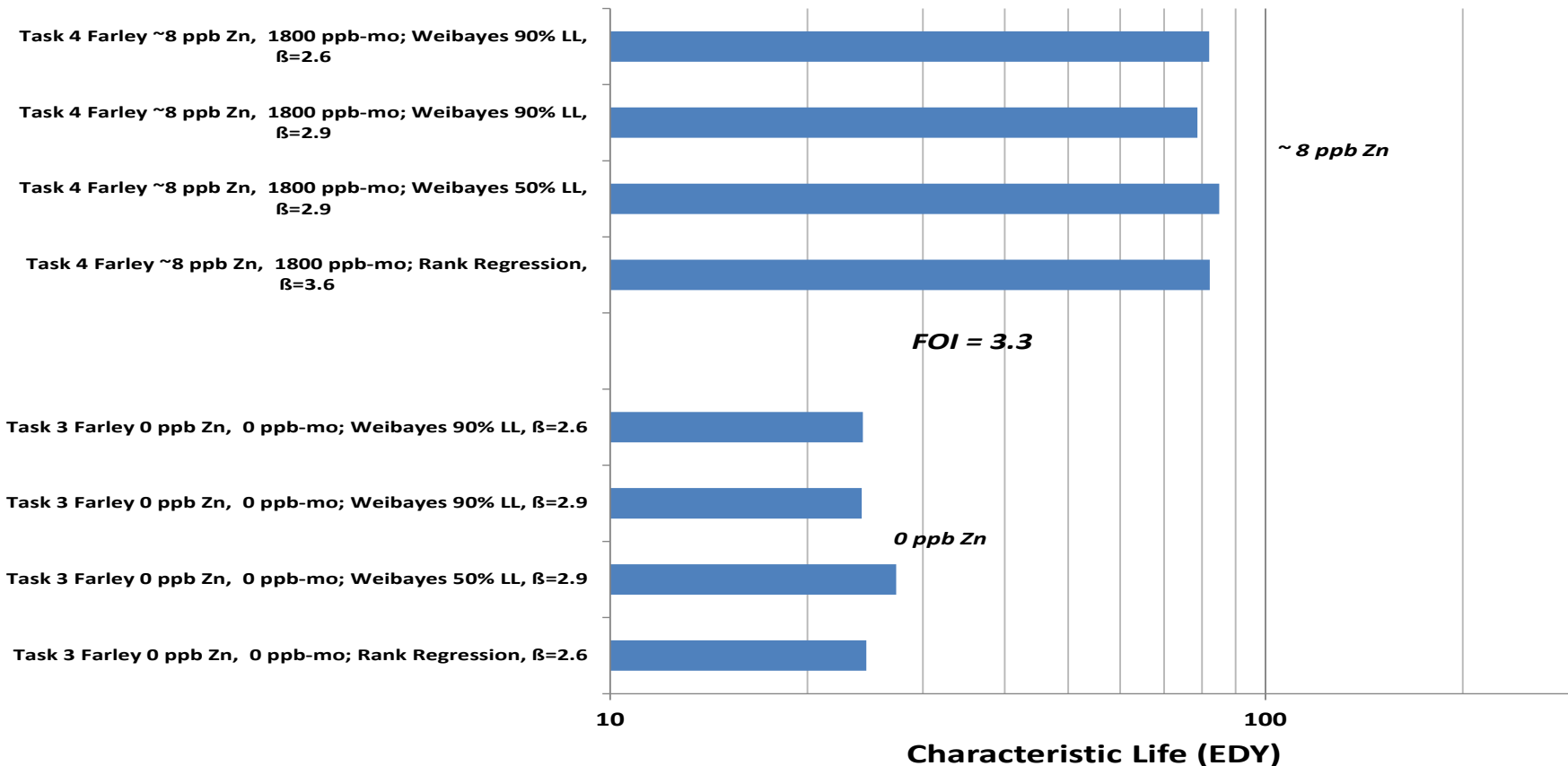
Example Comparison

Farley Alloy 600 Heat M3935

PA-MSC-0257R1



PWSCC of Alloy 600: with and without Zinc



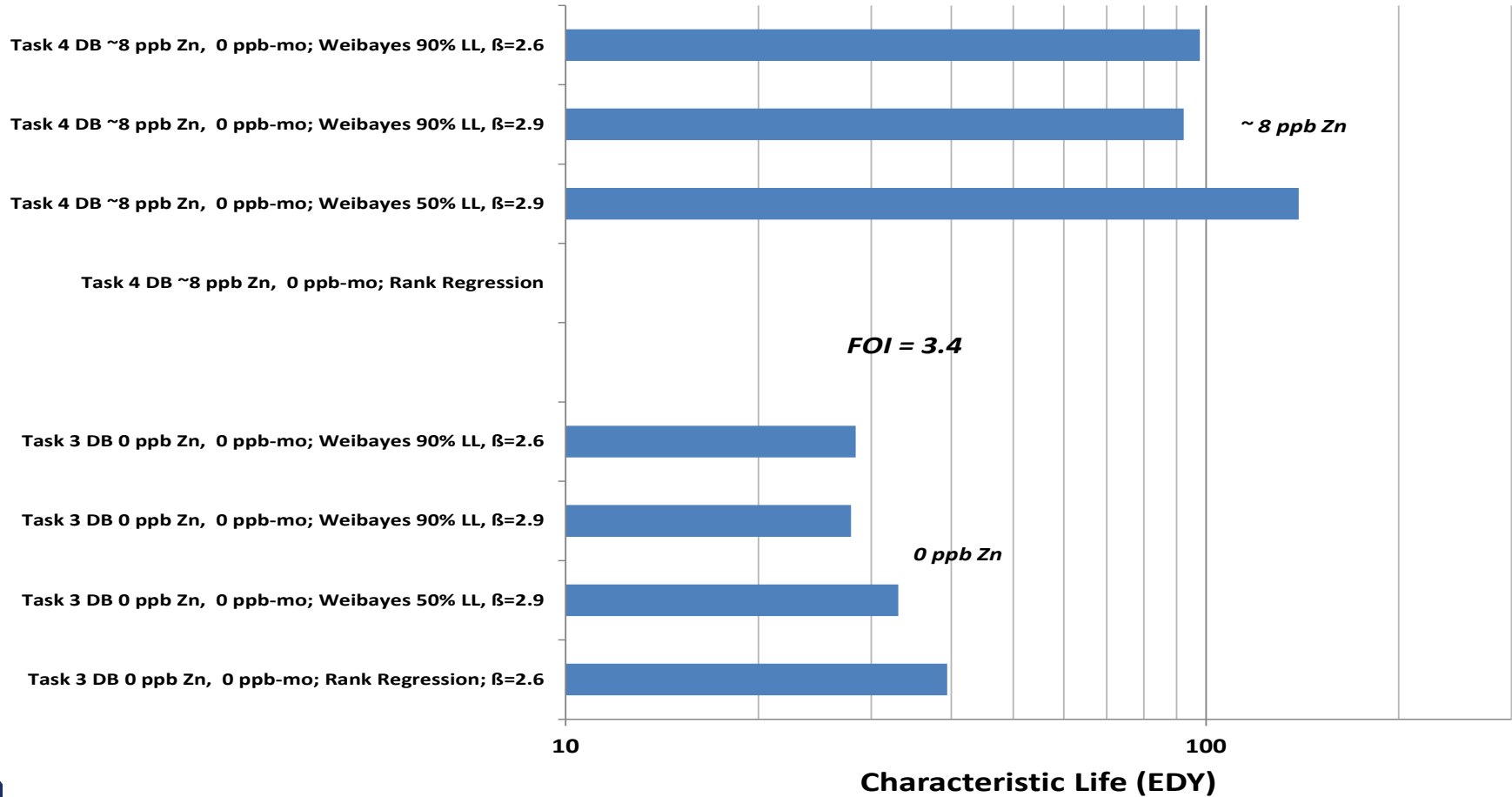
Example Comparison

Davis Besse Alloy 600 Heat M3935

PA-MSC-0257R1



PWSCC of Alloy 600: with and without Zinc



Example Comparison

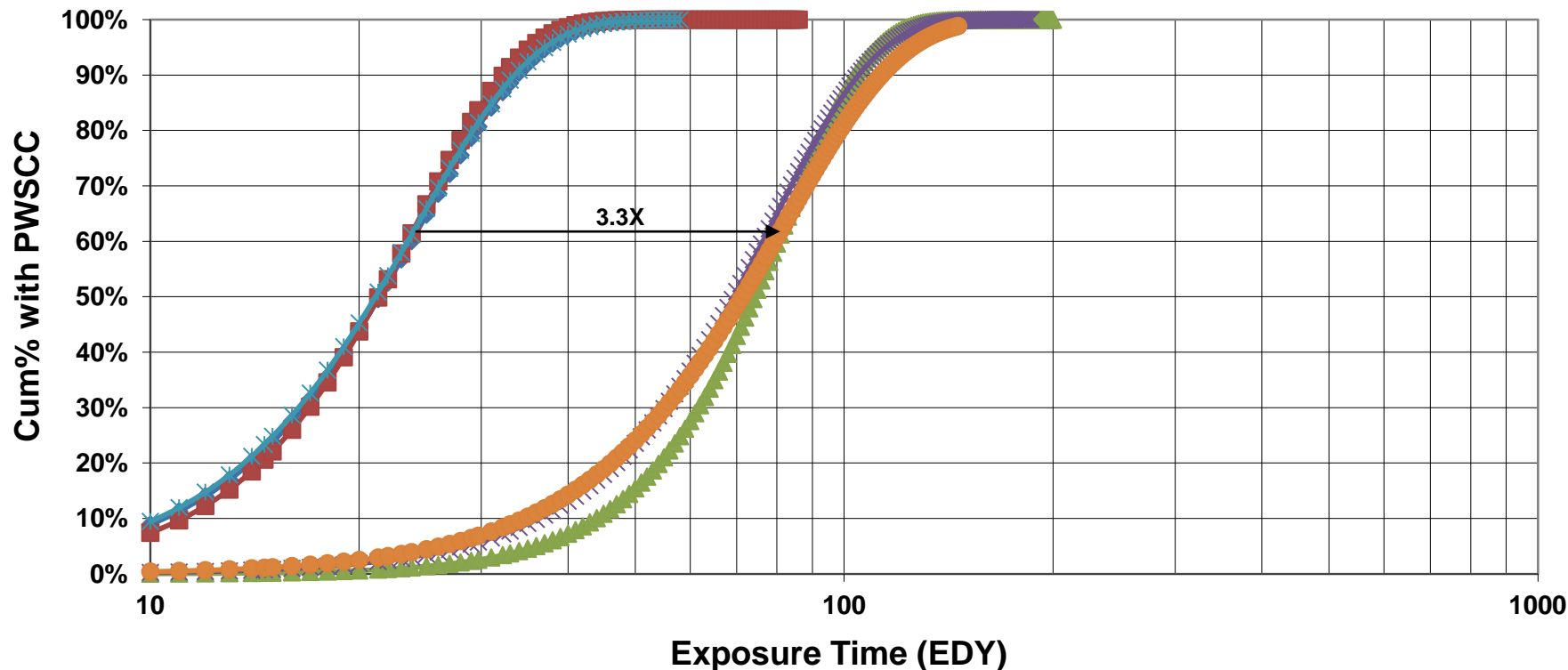
Farley Alloy 600 Heat M3935

PA-MSC-0257R1



Farley Alloy 600 M3935 PWSCC Initiation Trend - FOI with Zinc Addition

- ◆ Task 3 Baseline; no zinc RR
- Task 3 Baseline; no zinc WB b=2.9; 90%LL
- ✦ Task 3 Baseline; no zinc WB b=2.6; 90% LL
- ▲ Task 4 1800 ppb-mo zinc + ~8 ppb zinc RR
- ✦ Task 4 1800 ppb-mo zinc+ ~8 ppb WB b=2.9; 90%LL
- Task 4 1800 ppb-mo zinc + ~8 ppb WB b=2.6; 90% LL



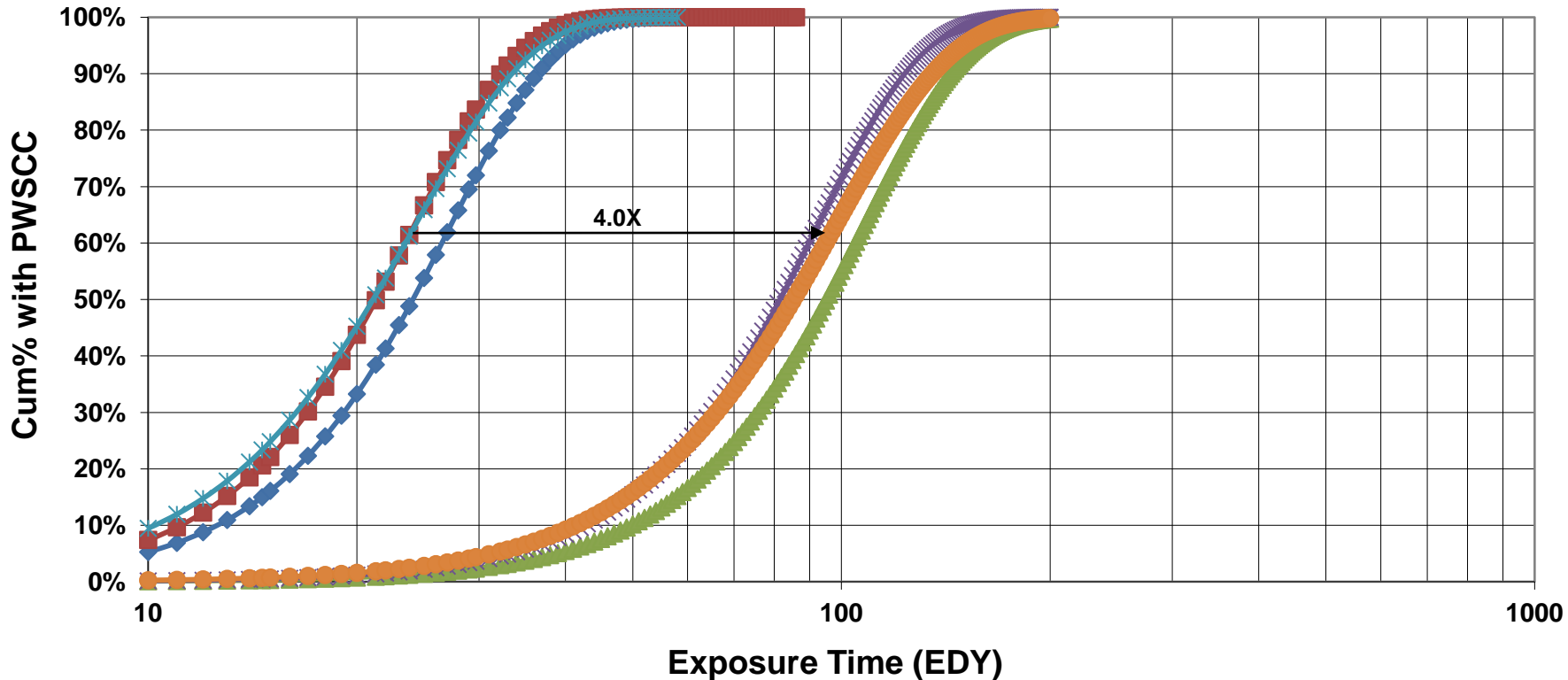
Example Comparison

PA-MS-C-0257R1

Farley Alloy 600 Heat M3935

Farley Alloy 600 M3935 PWSCC Initiation Trend - FOI with Zinc Addition

- ◆ Task 3 Baseline; no zinc WB b=2.9; 50% LL
- ◆ Task 3 Baseline; no zinc WB b=2.9; 90%LL
- ◆ Task 3 Baseline; no zinc WB b=2.6; 90% LL
- ◆ Task 4 275 ppb-mo zinc + ~8 ppb zinc WB b=2.9; 50% LL
- ◆ Task 4 275 ppb-mo zinc+ ~8 ppb WB b=2.9; 90%LL
- ◆ Task 4 275 ppb-mo zinc + ~8 ppb WB b=2.6; 90% LL



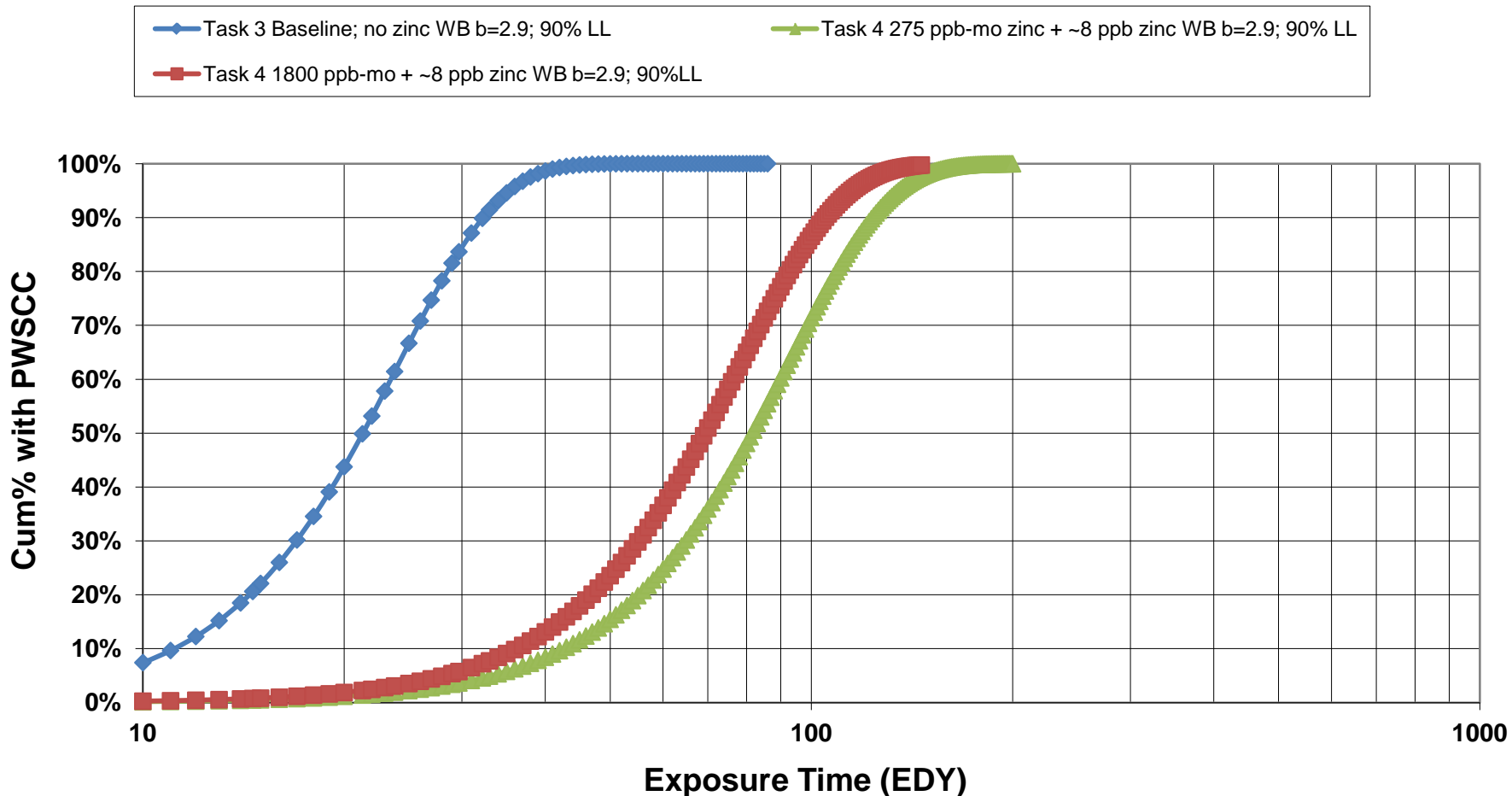
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Farley Alloy 600 PWSCC Initiation Trend - FOI with Zinc Addition



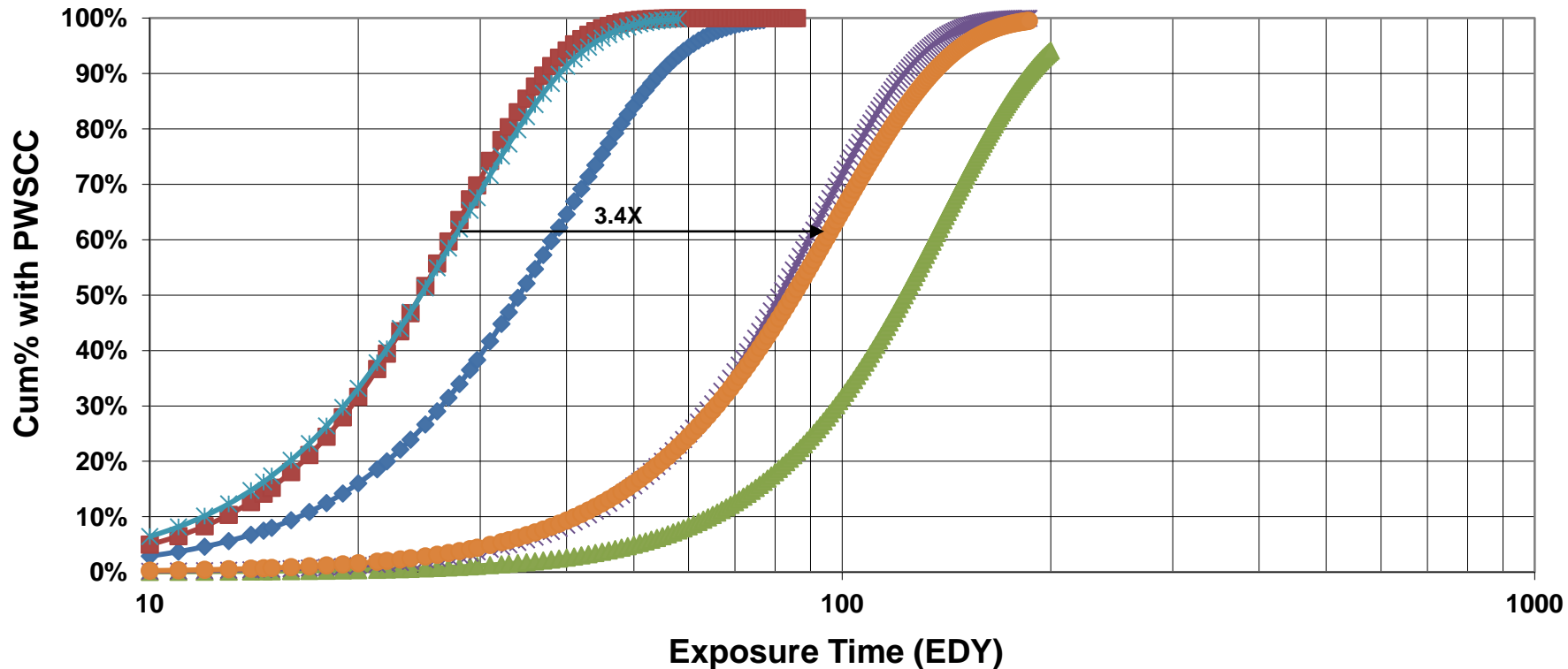
Example Comparison

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Davis Besse Alloy 600 Heat M3935

Davis Besse Alloy 600 M3935 PWSCC Initiation Trend - FOI with Zinc Addition

- ◆ Task 3 Baseline; no zinc RR
- Task 3 Baseline; no zinc WB b=2.9; 90%LL
- * Task 3 Baseline; no zinc WB b=2.6; 90% LL
- ▲ Task 4 0 ppb-mo zinc + ~8 ppb zinc WB 2.9; 50% LL
- ✕ Task 4 0 ppb-mo zinc+ ~8 ppb WB b=2.9; 90%LL
- Task 4 0 ppb-mo zinc + ~8 ppb WB b=2.6; 90% LL

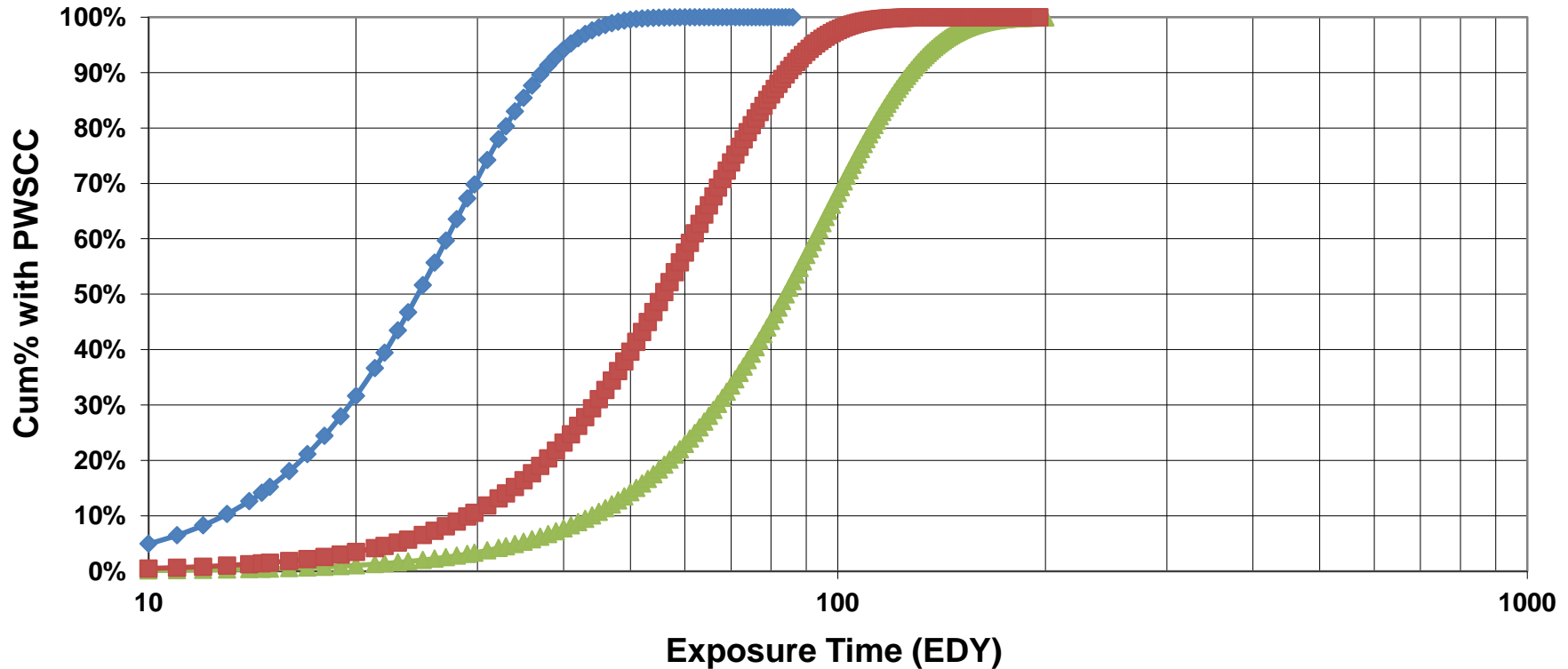


Example Comparison

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Davis Besse Alloy 600 Heat M3935

Davis Besse Alloy 600 PWSCC Initiation Trend - FOI with Zinc Addition

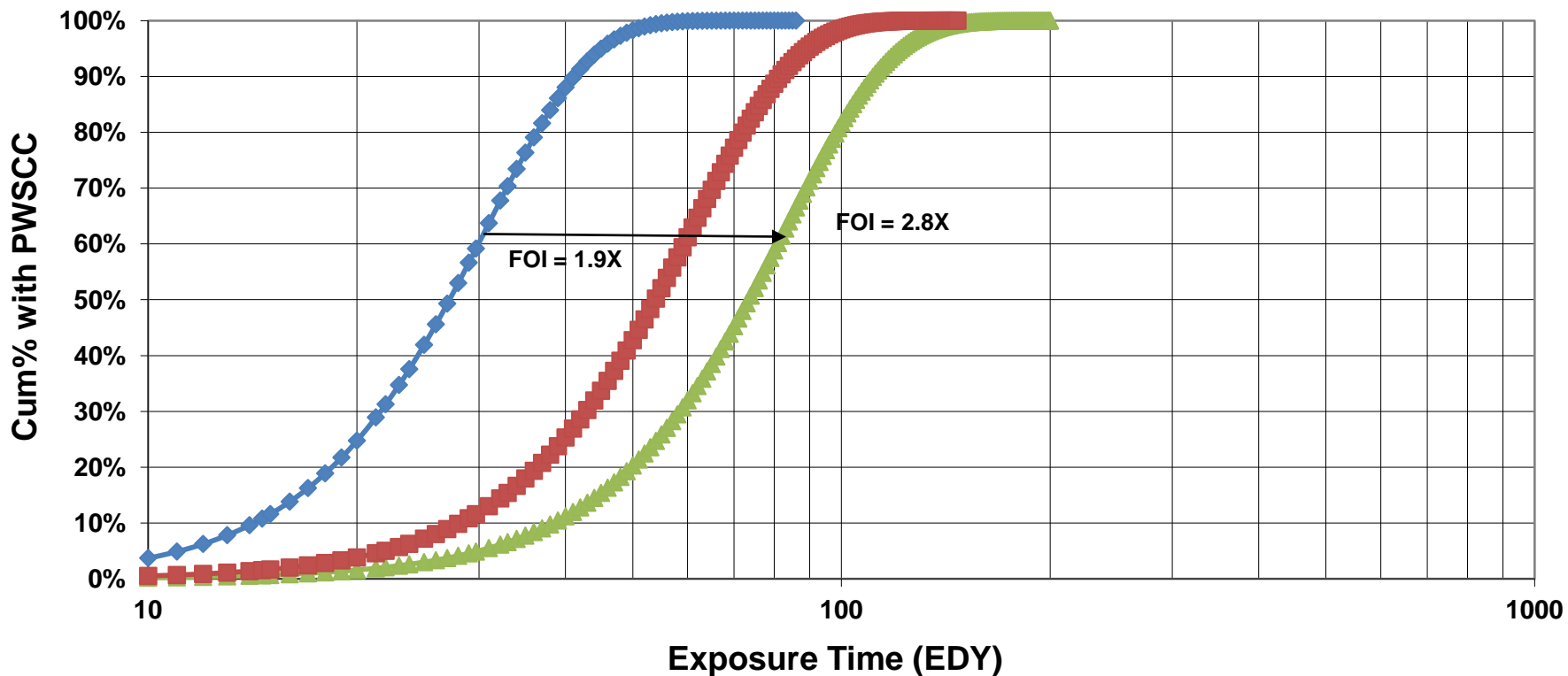


Example Comparison

VC Summer Alloy 82 weld metal

VC Summer Alloy 82 PWSCC Initiation Trend - FOI with Zinc Addition

- Task 3 Baseline; no zinc WB b=2.9; 90% LL
- Task 4 275 ppb-mo zinc + ~8 ppb zinc WB b=2.9; 90% LL
- Task 3 Baseline+ Task 4 zinc WB b=2.9; 90%LL

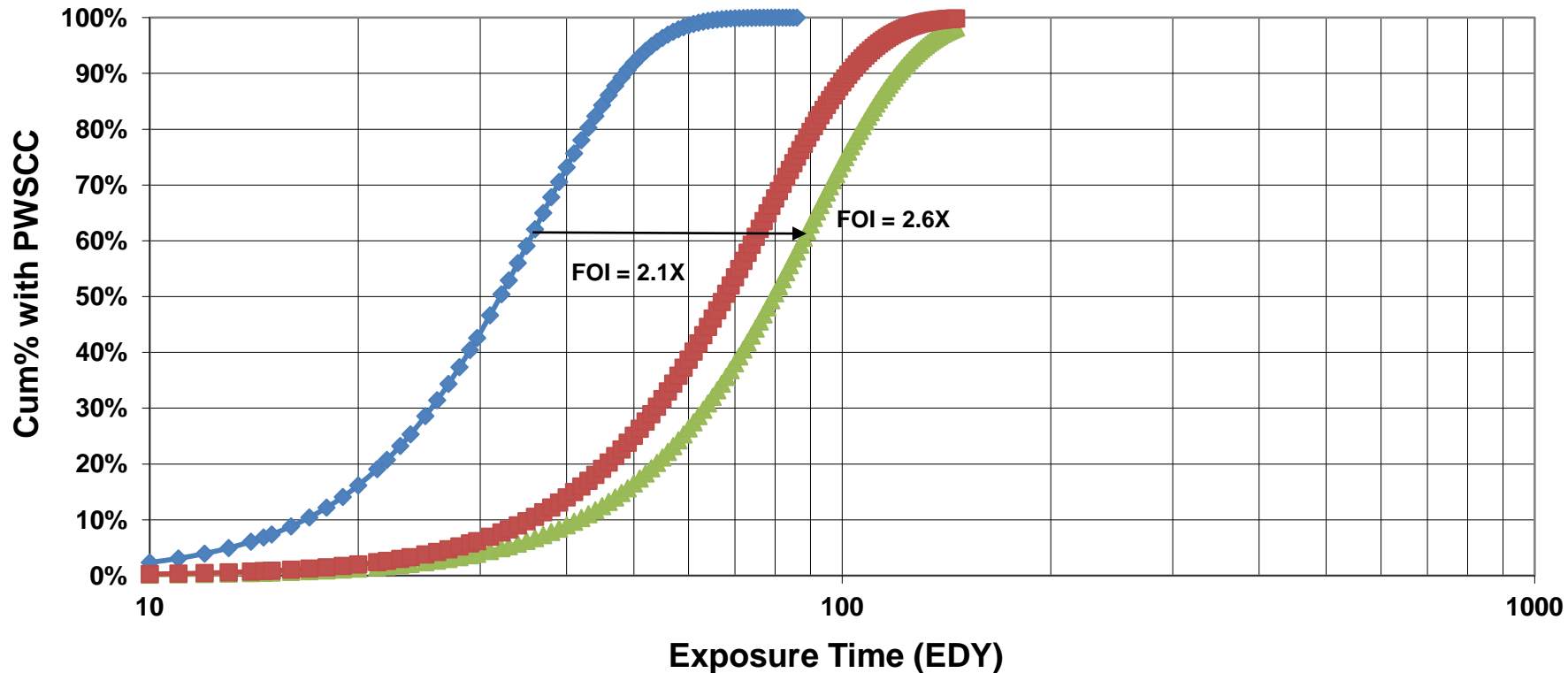


Example Comparison

VC Summer Alloy 182 weld metal

VC Summer Alloy 182 PWSCC Initiation Trend - FOI with Zinc Addition

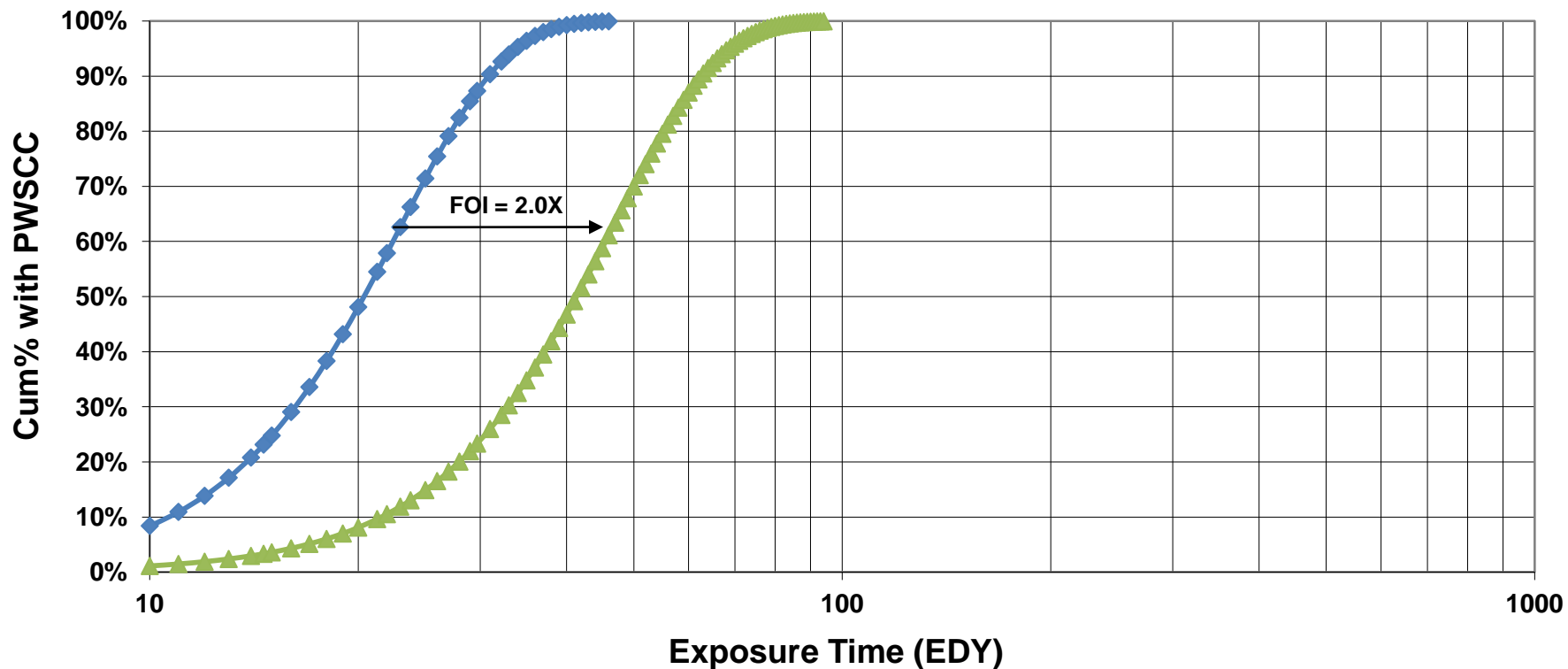
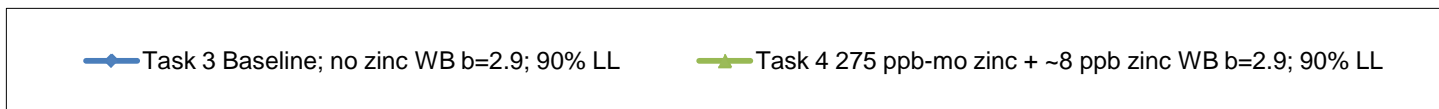
- Task 3 Baseline; no zinc WB b=2.9; 90% LL
- Task 4 275 ppb-mo zinc + ~8 ppb zinc WB b=2.9; 90% LL
- Task 3 Baseline + Task 4 zinc WB b=2.9; 90%LL



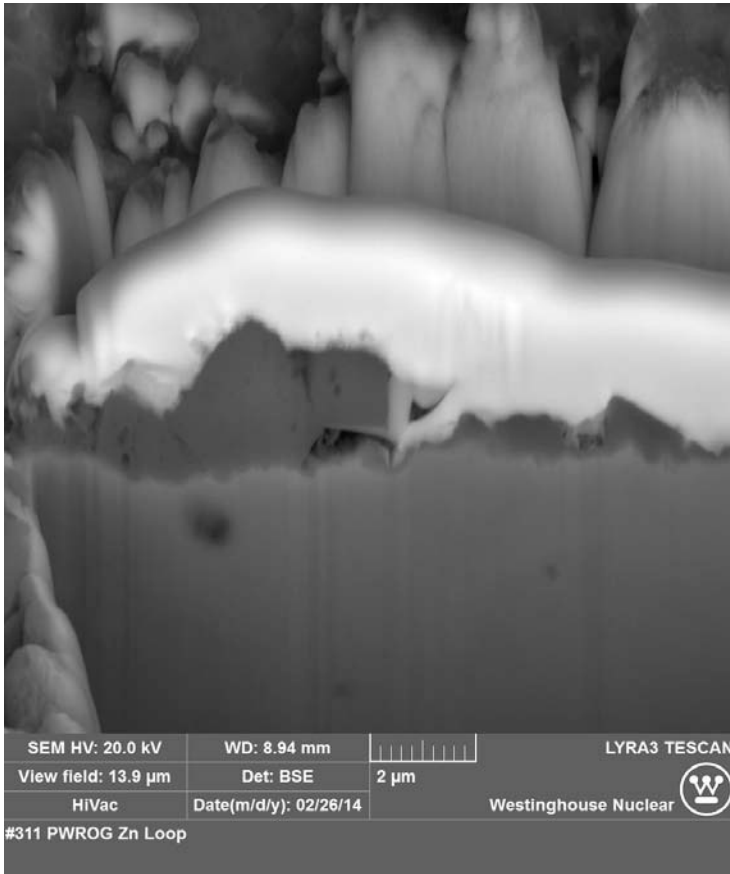
Example Comparison

Archive Alloy 152 weld

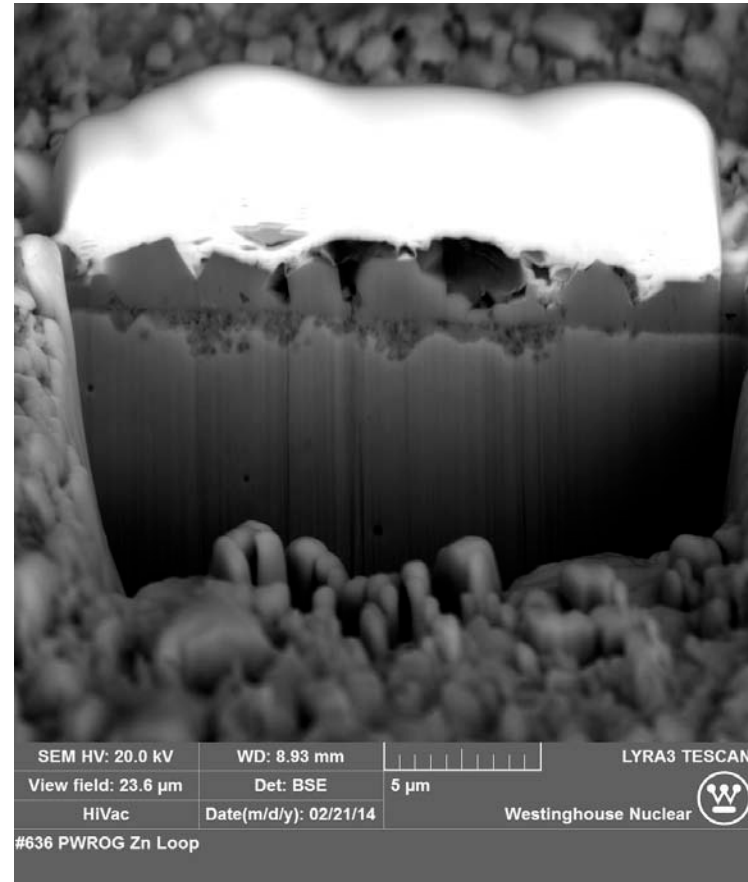
Archive Alloy 152 PWSCC Initiation Trend - FOI with Zinc Addition



Using FIB/SEM to study how PA-MSC-0257R1 zinc changes the passive film



Farley Alloy 600



Alloy 152

Characteristic PWSCC PA-MSC-0257R1

Initiation Times

- Based on similar Weibull/Weibayes analyses, an estimate of Weibull characteristic life determined
- Clear benefit of delayed PWSCC initiation achieved with zinc addition
- Recall that Weibull characteristic life occurs when ~62% of samples have initiated

	Far#14/16	DB#2 OD	Summer 182	Summer 82	690	52M	152
Task 3 results (control, 0 zinc) # PWSCC/Total at 24+ EDY	~25.1	~32.2	~40.6	~34.3	32.1-48.6	29.7-45.0	~31.0
Starting Σ[Zinc]	at 55.6 EDY or 80.2 EDY		63.8 or 88.4 EDY		at 55.6 EDY or 80.2 EDY		
1800 - 2000 ppb-mo Zn	75.5 - 82.0						
275 - 475 ppb-mo Zn	~99.6	~107.4	~107	~98.5	nd	nd	nd
150- 350 ppb-mo Zn		~85.6					
0 - 200 ppb-mo Zn		102.9-139			67.3-102	72.6-110	~50.9
0 ppb-mo T3 Beams with no PWSCC & 24 0 - 200 ppb-mo Zn		~91.8			nd		nd
275 ppb-mo Task 3 Beams with no PWSCC & 24 EDY 275 - 475 ppb-mo Zn	86.3 - 107		~85.1	~66.1	nd	nd	nd

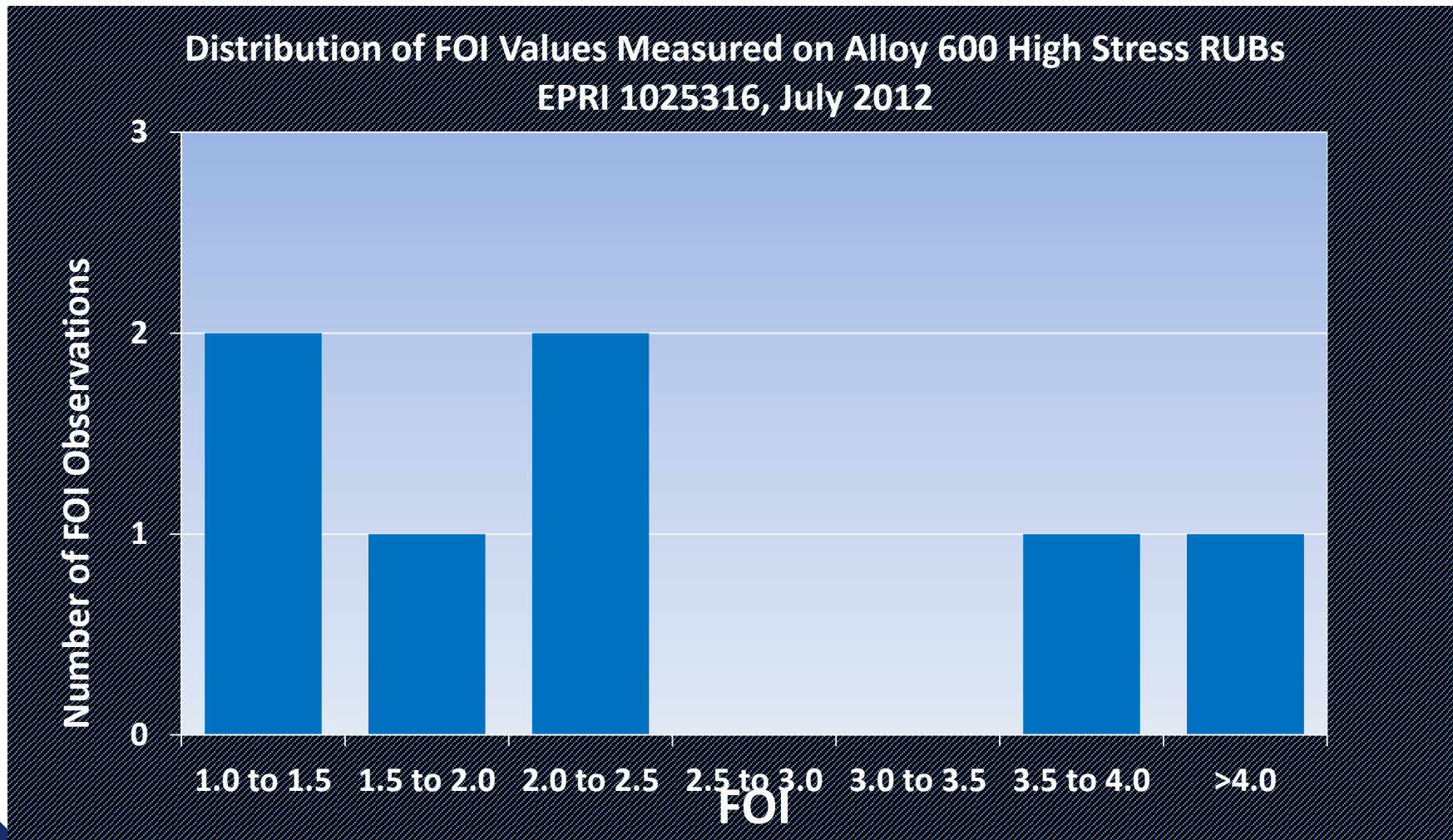
FOI with Zinc

- An estimate of the FOI calculated for cases with sufficient data

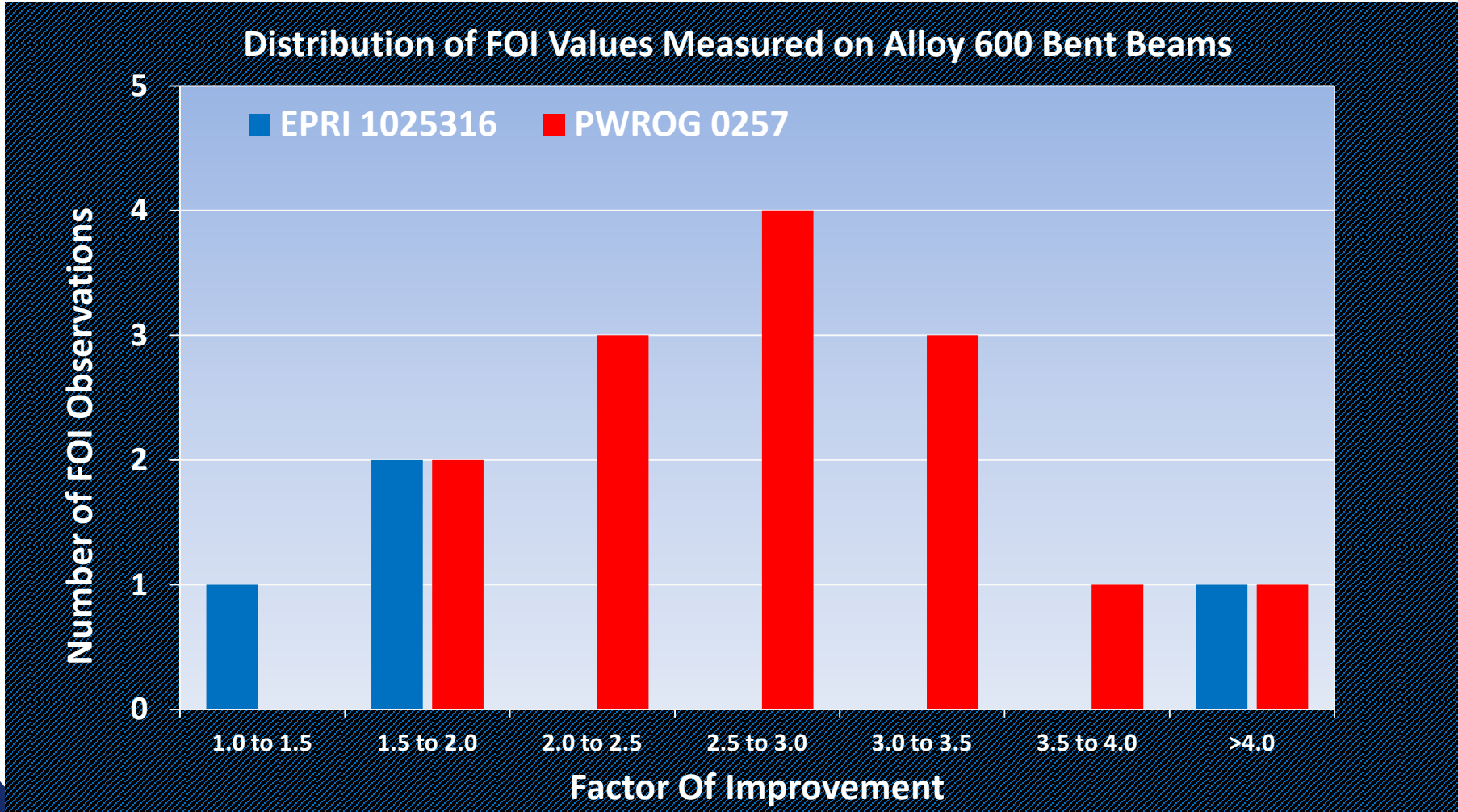
	Far#14/16	DB#2 OD	Summer 182	Summer 82	690	52M	152
Task 3 results (control, 0 zinc) # PWSCC/Total at 24+ EDY	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Starting Σ[Zinc]	at 55.6 EDY or 80.2 EDY		63.8 or 88.4 EDY		at 55.6 EDY or 80.2 EDY		
1800 - 2000 ppb-mo Zn	3.0 - 3.3						
275 - 475 ppb-mo Zn	~4.6	~3.3	~2.6	2.9	nd	nd	nd
150- 350 ppb-mo Zn		~2.7					
0 - 200 ppb-mo Zn		3.2 - 4.3			~2.1	~2.4	~1.6
0 ppb-mo T3 Beams with no PWSCC & 24 0 - 200 ppb-mo Zn		~2.9			nd		nd
275 ppb-mo Task 3 Beams with no PWSCC & 24 EDY 275 - 475 ppb-mo Zn	3.4 - 4.3		~2.1	~1.9	nd	nd	nd

Comparison with prior EPRI FOI data – lab

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Comparison with prior PA-MSC-0257R1 EPRI FOI data – lab



Comparison with prior PA-MSR-0257R1 FOI data – field SG tubes

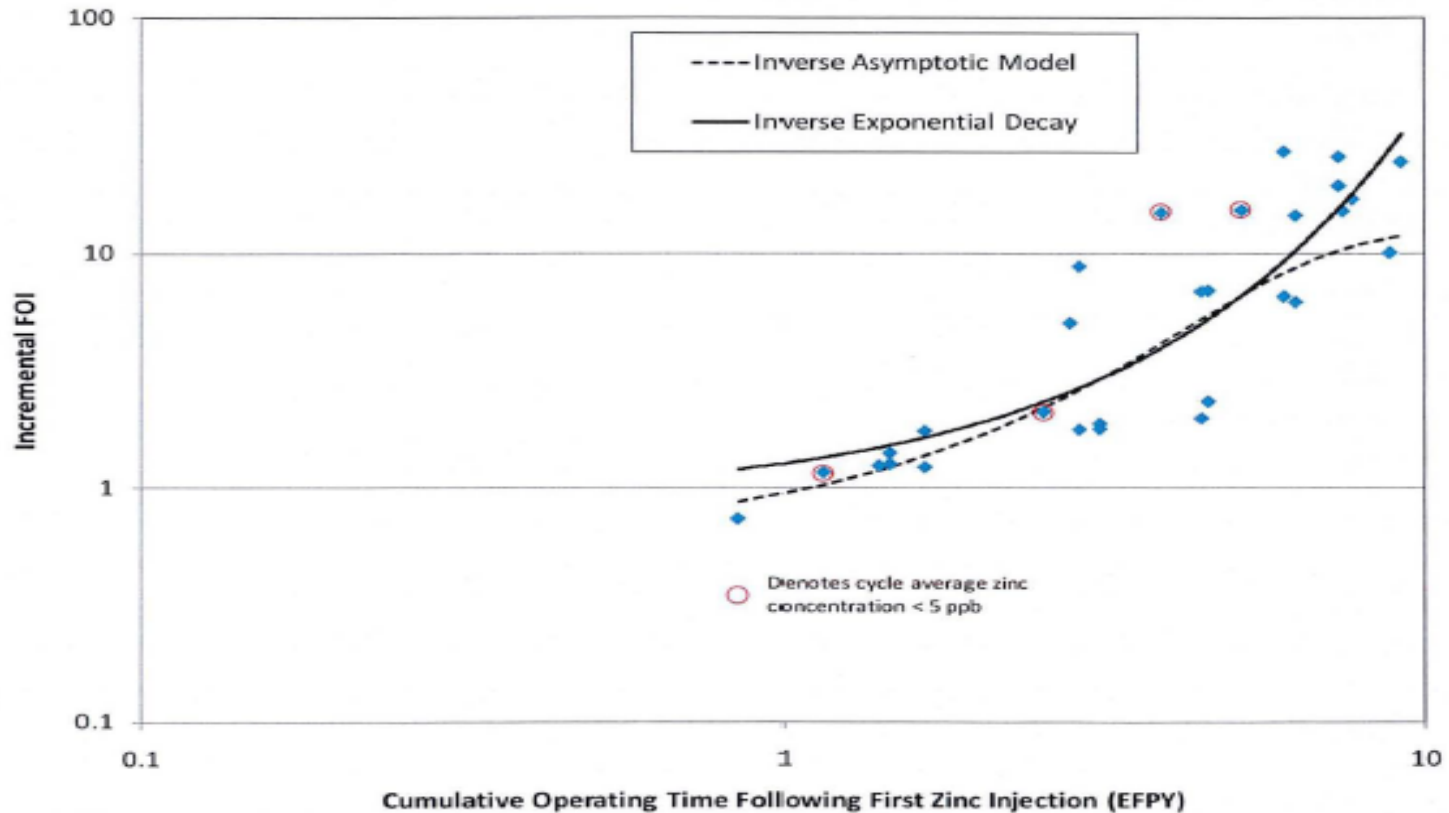


Figure 2-26
Incremental Factor of Improvement vs. Cumulative Operating Time Following First Zinc Injection

Conclusions

- Zinc addition is effective in delaying PWSCC initiation in Alloy 600 and the associated weld metals
- Initial estimates of approximately 300 ppb-months of zinc exposure appears to be needed for a marked improvement in PWSCC initiation time
- Improvements in time to PWSCC initiation by approximately a factor of 3 were indicated in long term experiments for Alloy 600
- Lower Factors of Improvements measured for the associated weld materials
- Benefits observed for zinc exposure of materials that had experienced ~24 EDY exposure prior to zinc addition
- Anticipate that the results of this program can be used in an xLPR model of component life

Summary

- The experimental testing dedicated to PWSCC initiation in zinc in a well-controlled environment generated ~56 EDY equivalent exposure (at 600°F)
- The results of the testing are in reasonable agreement with expectations at the onset of the program with factors of improvement (FOI) values falling within the expected range.
- The quantitative comparable performance of the test materials with and without zinc are expected to be applicable and supportive of the overall goal of regulatory acceptance of zinc as a chemical mitigation method

Questions?

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