



U.S. Army Research, Development and
Engineering Command

Development of Life Prediction Models for High Strength Steel in a Hydrogen Emitting Environment



TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

ASETS Defense 2012

August 28-30, San Diego, CA

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Report Documentation Page				Form Approved OMB No. 0704-0188	
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1. REPORT DATE 2012		2. REPORT TYPE		3. DATES COVERED 00-00-2012 to 00-00-2012	
4. TITLE AND SUBTITLE Development of Life Prediction Models for High Strength Steel in a Hydrogen Emitting Environment				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Research Laboratory, Aberdeen Proving Ground, Adelphi, MD, 20783				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES Presented at the ASETS Defense 2012: Workshop on Sustainable Surface Engineering for Aerospace and Defense August 27-30, 2012, San Diego, CA					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 27	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

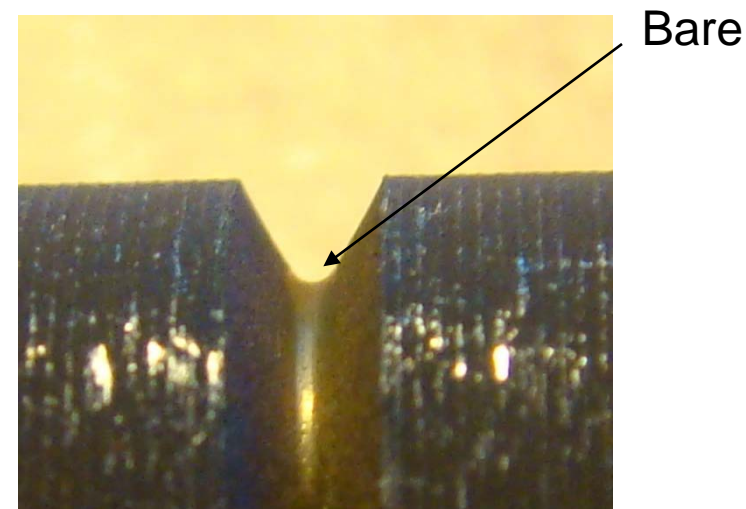
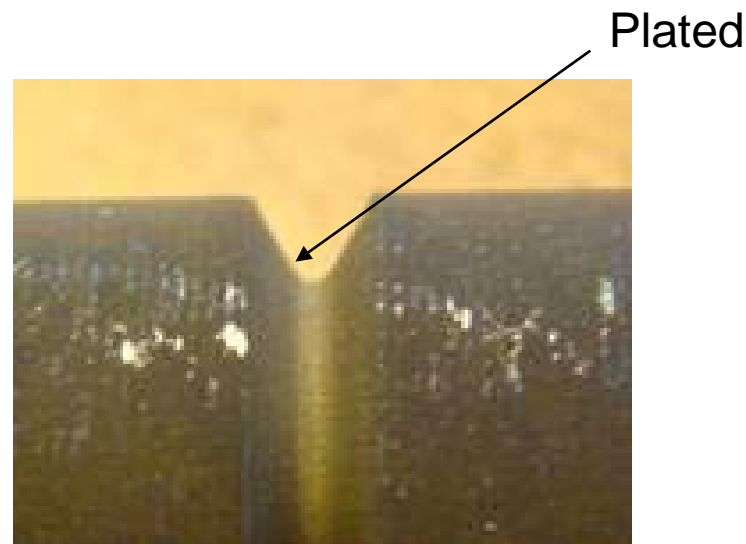
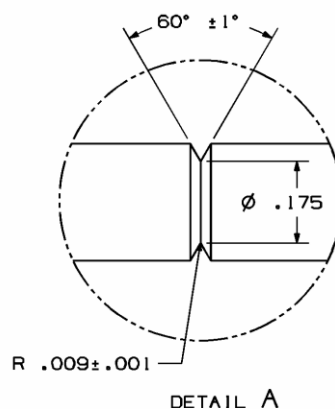
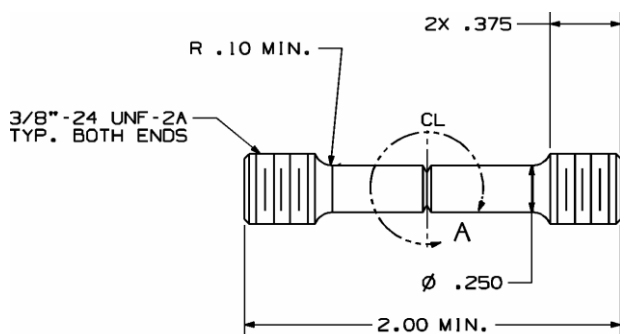
Project Team

- **PI – Scott Grendahl, USARL, APG, MD**
- **The Boeing Company**
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 - Joe Osborne, Seattle, WA
 - Stephen Jones, Seattle, WA
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- **Chad Hogan, HAFB OO-ALC, Ogden, UT**
- **Richard Green, GSS, Ft. Worth, TX**
- **Dave Kelly, ASKO Plating, Seattle, WA**
- **ASTM F07.04 committee on Hydrogen Embrittlement**

Technical Objective

- Increase the implementation and utilization of environmentally friendly maintenance chemicals and cadmium alternatives by alleviating the HE obstacle.
- FY10 – Life models for air-melted AMS 6415 4340 steel
- FY11 – Life models for aerospace AMS 6414 grade 4340 steel
- FY12 – Life models for prospective maintenance chemicals
- FY13 – Life models for prospective alternative coatings

ASTM F 519 Type 1a.1 Test Specimen



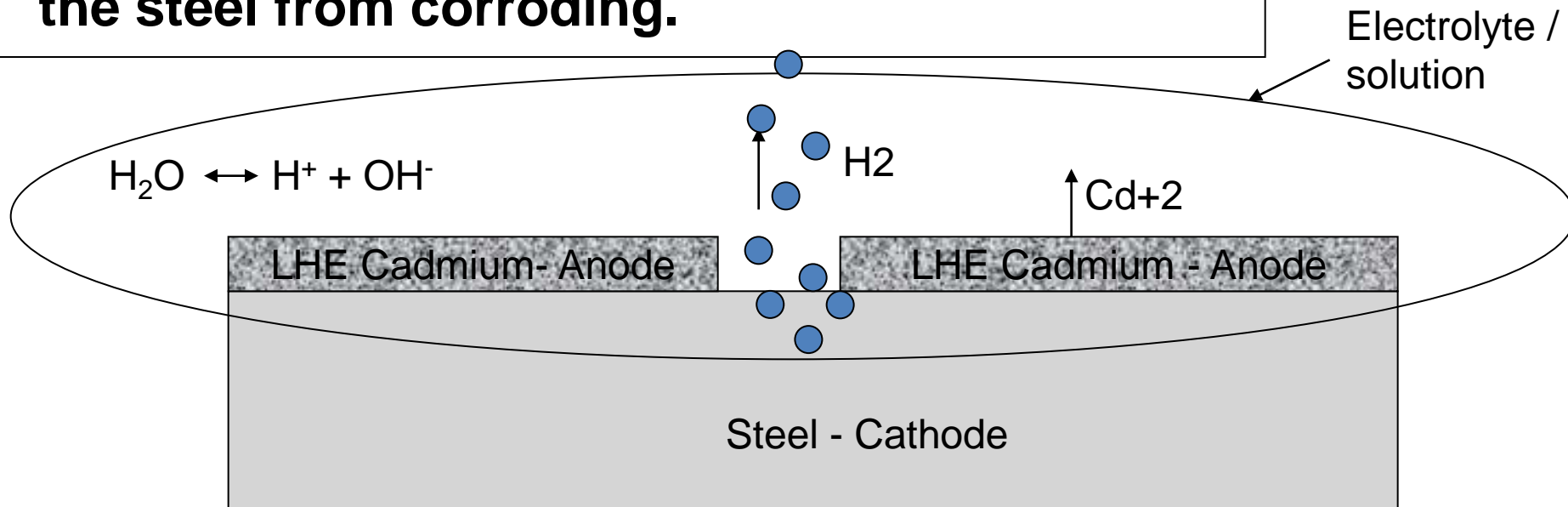
Cd Plated Notch



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Cd Protection Mechanism

- Cd is sacrificial to steel. It corrodes to prevent the steel from corroding.**



Porous Cd creates microscopic voids or thin areas that allow solutions (electrolyte) to come in contact with steel surface.

Solution forms galvanic cell between steel and Cd – the following RXNs occur:

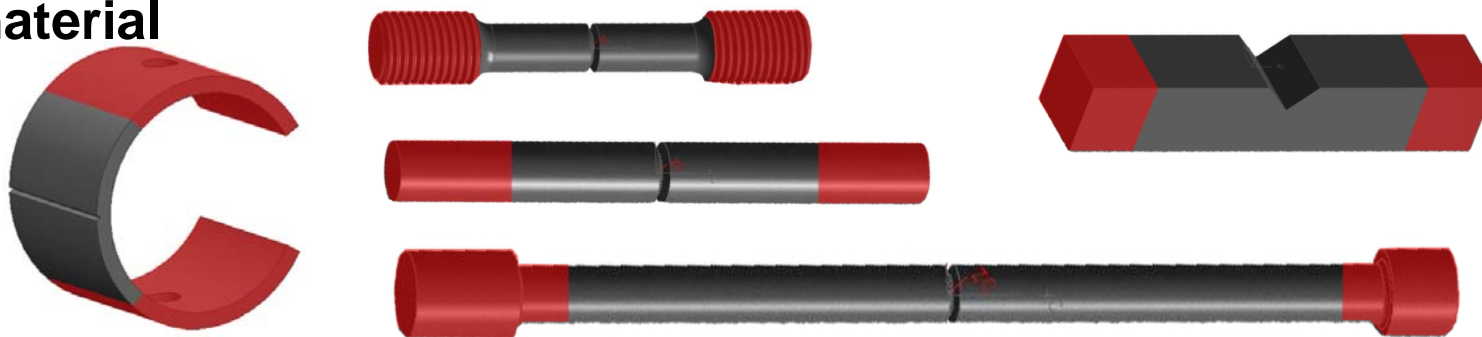


STEEL IS PROTECTED BY FORMATION OF HYDROGEN!

- 1977 – Work carried-out to develop a re-embrittlement test for ASTM F 519
 - Round Robin testing conducted by Lockheed, Douglas and Boeing aircraft companies.
 - Water used as control to determine test conditions for qualifying maintenance fluids
 - 45% NFS for 150 hours was established as a test criteria for maintenance fluids
 - LHE Cd Plated Type 1a (notch) specimens at 45% NFS will fail this test when exposed to water
 - Salt should be worse than water

Technical Approach

- HE testing has traditionally been done pass/fail on worst case material

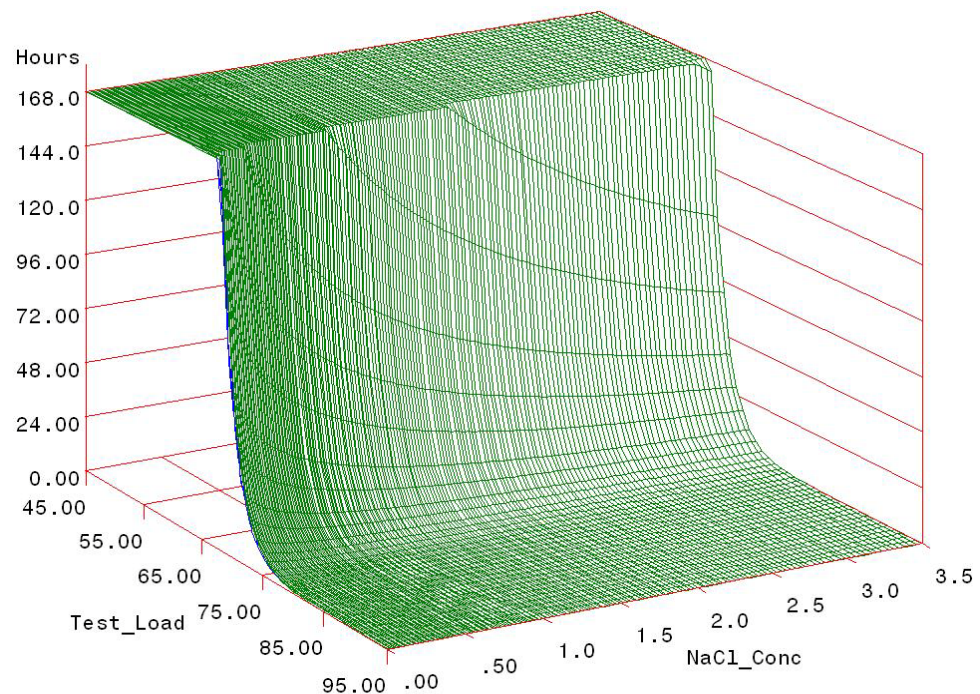


- DoE approach develops life prediction models over a range of material strength, applied stress, and environment
 - ◆ 280 ksi
 - ◆ Stress varies with geometry
 - ◆ Cad plated steel
- Vs.
 - 140 - 280 ksi
 - 40 - 95% NFS
 - % of NaCl, or Conc. or Plating
- Statistical analysis allows a reasonable matrix size while accounting for full spectrum of variables with prediction.
 - ◆ 5x5x5x5 (625) Vs. • 400

DoE Technical Approach

Predicted Median Lifetime
Strength=T5 (280 KSI)

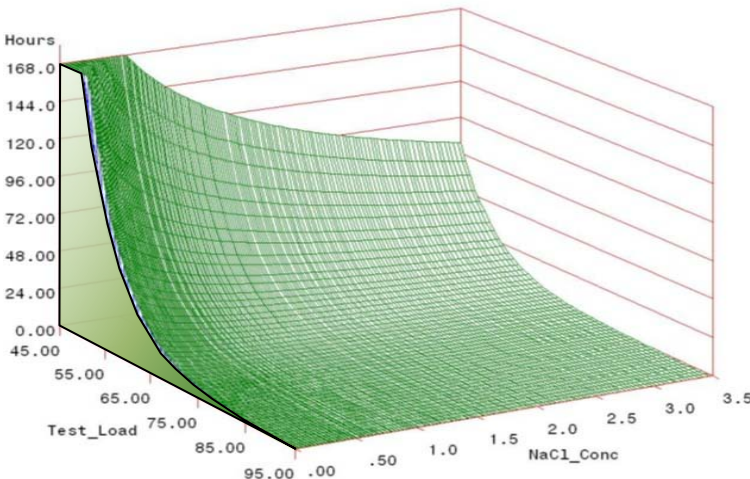
- Material Strength (140 - 280 ksi)
- Applied Stress (% of NFS)
- Environment
 - Wt.% of NaCl
 - Conc. of chemical
 - Thickness of coating
- Model Yields - TTF (Time to Failure)



ASTM F 519 Type 1c Original

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Predicted Median Lifetime Strength=T5 (280 KSI)



- Traditionally was a pass/fail evaluation
- Failure caused coatings/chemicals not to be implemented
- Models reveal safety zone (below curves)
- Data derived over a range of material strength levels

- This strength level won't tolerate greater than 50% of its UTS without the possibility of H₂ compromise from even a minimal H₂ source
- Must coat to minimize environmental corrosion, limit H₂ maintenance processes, or accept risk of failure during component life
- Empirical models help answer the common designer questions:
 - Do I need to coat for corrosion protection?
 - Can electro-chemical coating processes be safely used without H₂ fear?
 - Can I acid pickle this steel to remove scale, corrosion?
 - Will aqueous cleaners affect performance of the steel?
 - Will weld cracking be a concern once fielded?

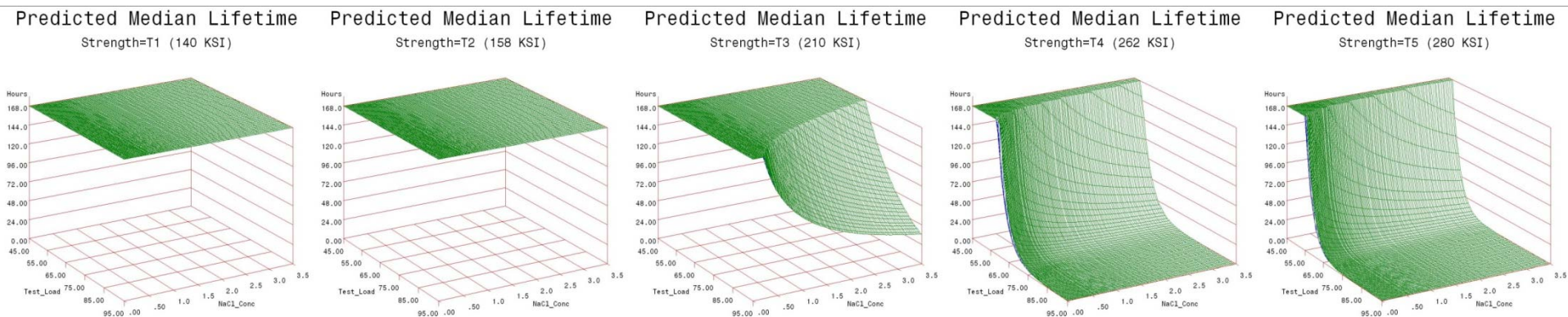
DoE Technical Approach

Condition	$-\alpha$	-	0	+	$+\alpha$
Strength (ksi)	140	158	210	262	280
Test Load (% NFS)	40	45	60	75	80
NaCl Concentration (wt% NaCl)	1.25E-05	0.01	0.50	2.36	3.5

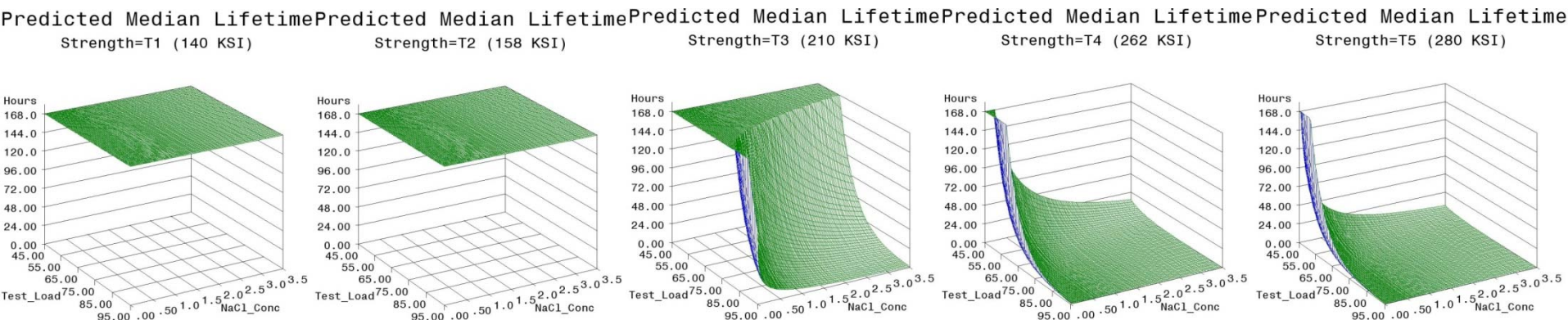
- Linear with Center points
- Quadratic
- Confirmation Runs
- Base model is developed from Linear and Quadratic portions
 - $\ln X = 19.01 - 11.67 * \text{strength} - 9.93 * \text{test_load} - 0.88 * \text{NaCl} + \text{offset}$
 - Run confirmations, then re-compute, then refine model

- Air-melt (SAE-AMS-6415), aerospace grade (SAE-AMS-6414) models were created for all geometries, heat treats, and applied stress
- Explore data to determine best geometry to assess maintenance chemicals, alternative coatings (worst case)
- Assess applicable maintenance chemicals or coatings in range of concentrations or thickness, etc.
- Results will provide the airworthiness authorities data to derive which processes (chemicals or coatings), or applications are deemed safe.

1a1 Results



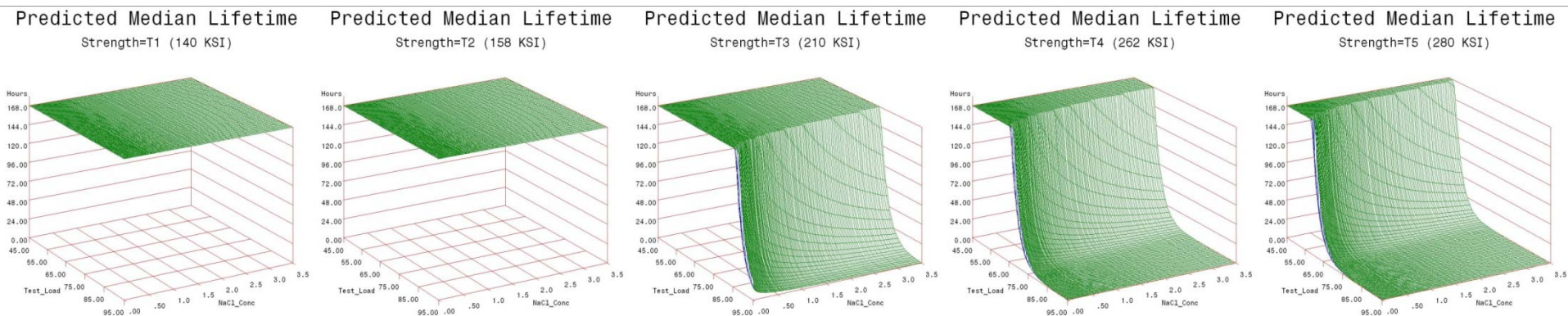
Air-melt 4340 - AMS-6415



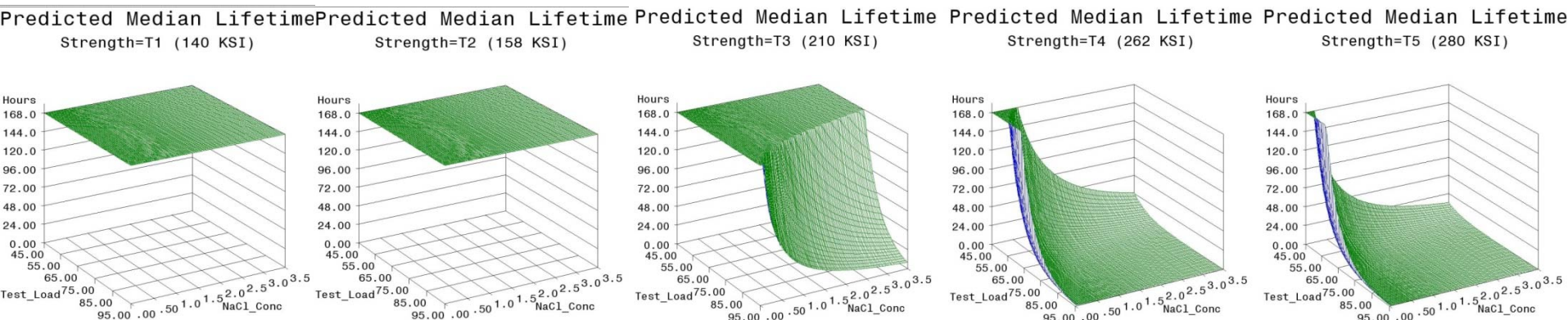
Aerospace 4340 - AMS-6414

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1a2 Results



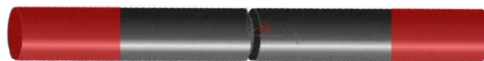
Air-melt 4340 - AMS-6415



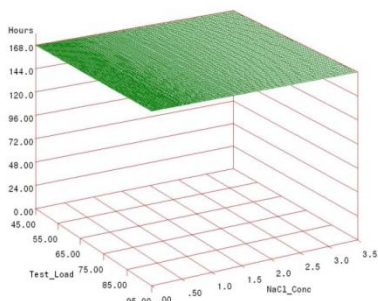
Aerospace 4340 - AMS-6414

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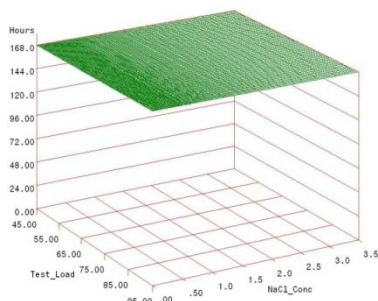
1c Results



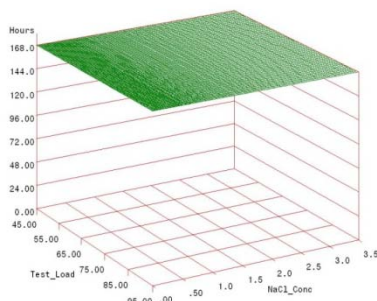
Predicted Median Lifetime
Strength=T1 (140 KSI)



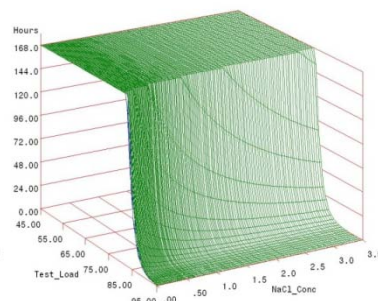
Predicted Median Lifetime
Strength=T2 (158 KSI)



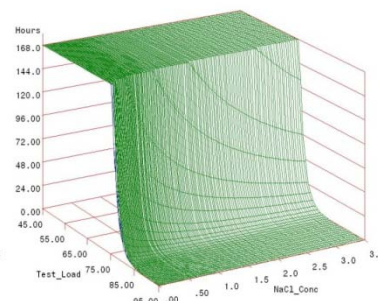
Predicted Median Lifetime
Strength=T3 (210 KSI)



Predicted Median Lifetime
Strength=T4 (262 KSI)

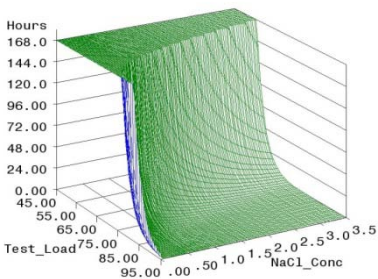
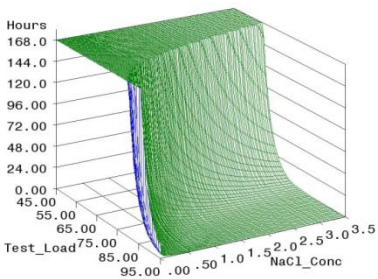
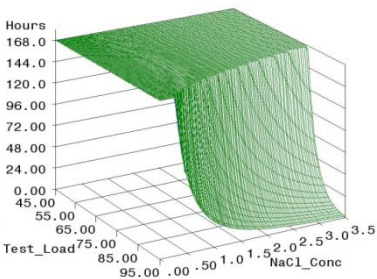
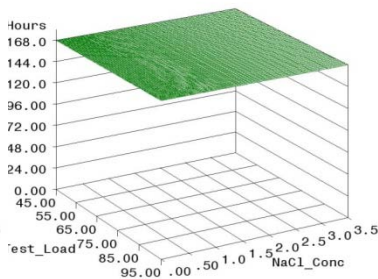
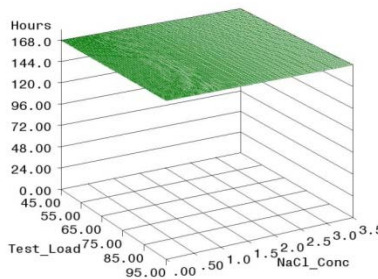


Predicted Median Lifetime
Strength=T5 (280 KSI)



Air-melt 4340 - AMS-6415

Predicted Median Lifetime Predicted Median Lifetime Predicted Median Lifetime Predicted Median Lifetime Predicted Median Lifetime
Strength=T1 (140 KSI) Strength=T2 (158 KSI) Strength=T3 (210 KSI) Strength=T4 (262 KSI) Strength=T5 (280 KSI)



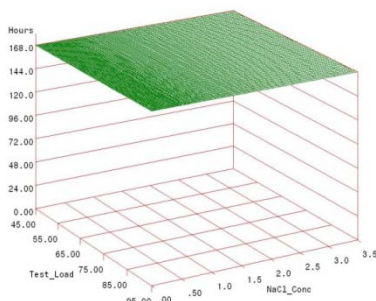
Aerospace 4340 - AMS-6414

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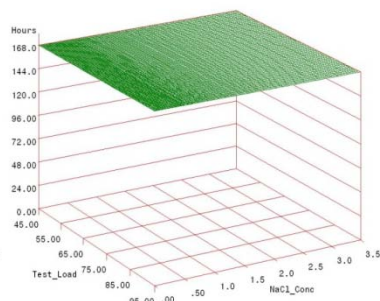
1d Results



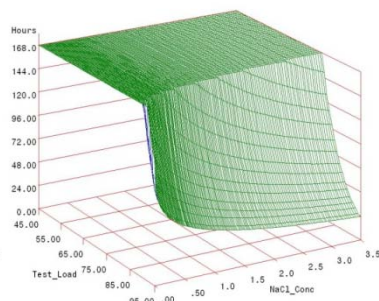
Predicted Median Lifetime
Strength=T1 (140 KSI)



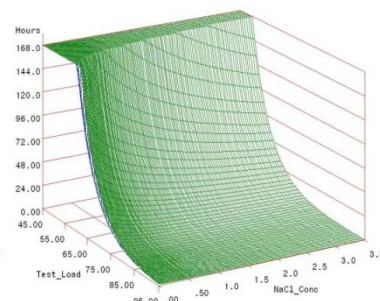
Predicted Median Lifetime
Strength=T2 (158 KSI)



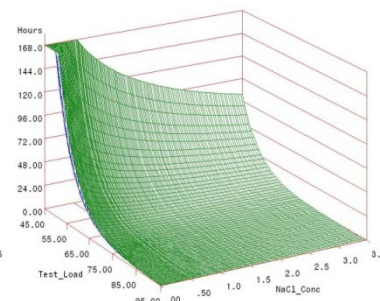
Predicted Median Lifetime
Strength=T3 (210 KSI)



Predicted Median Lifetime
Strength=T4 (262 KSI)

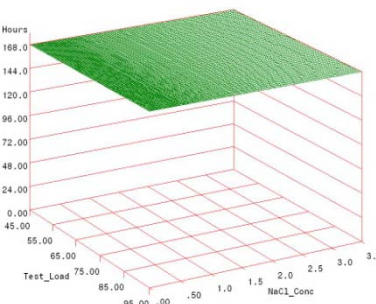


Predicted Median Lifetime
Strength=T5 (280 KSI)

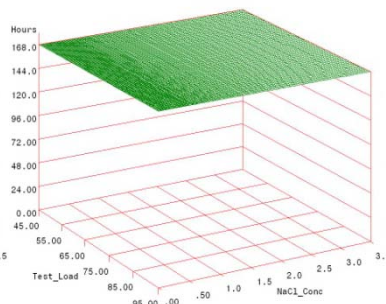


Air-melt 4340 - AMS-6415

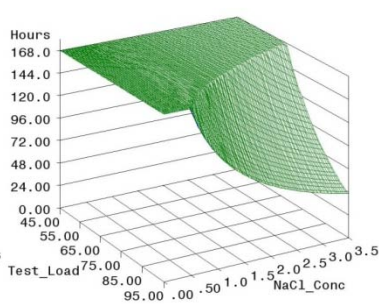
Predicted Median Lifetime
Strength=T1 (140 KSI)



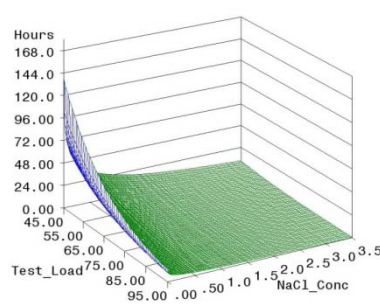
Predicted Median Lifetime
Strength=T2 (158 KSI)



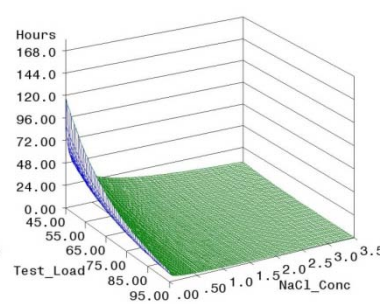
Predicted Median Lifetime
Strength=T3 (210 KSI)



Predicted Median Lifetime
Strength=T4 (262 KSI)



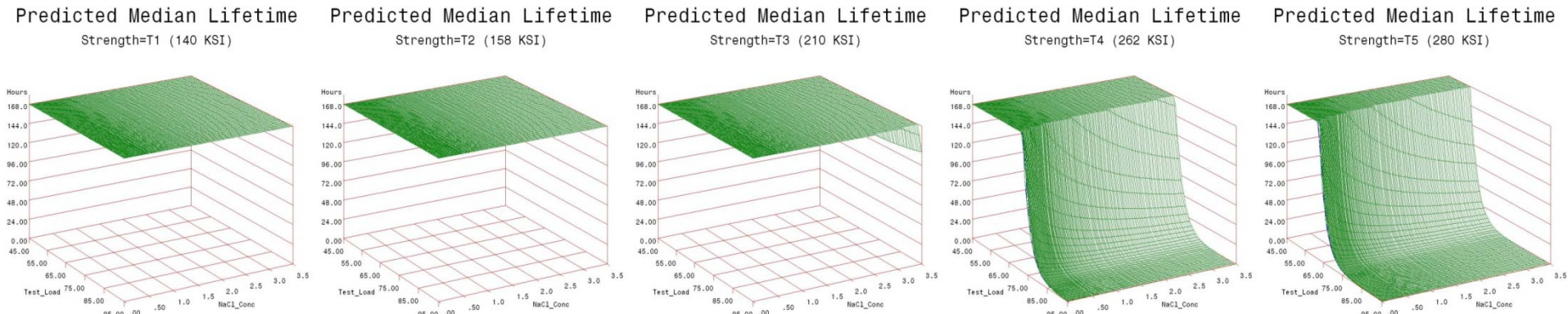
Predicted Median Lifetime
Strength=T5 (280 KSI)



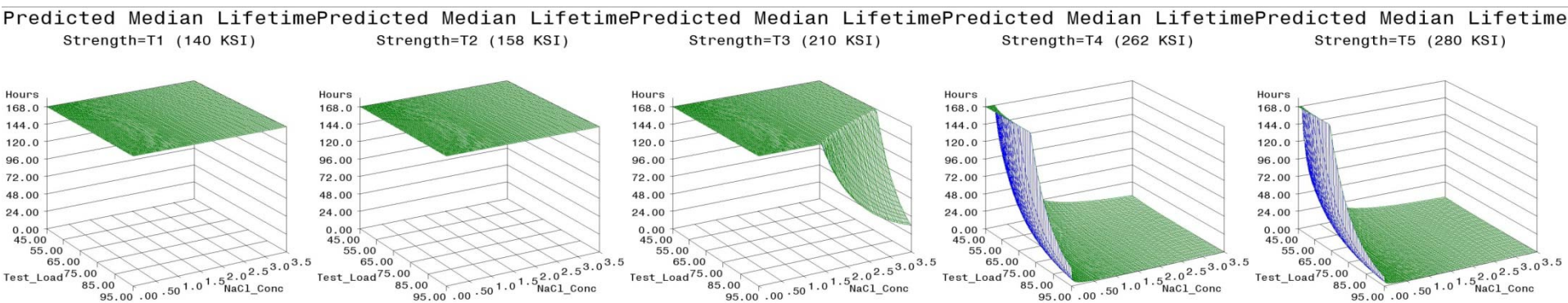
Aerospace 4340 - AMS-6414

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1e Results



Air-melt 4340 - AMS-6415



Aerospace 4340 - AMS-6414

TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

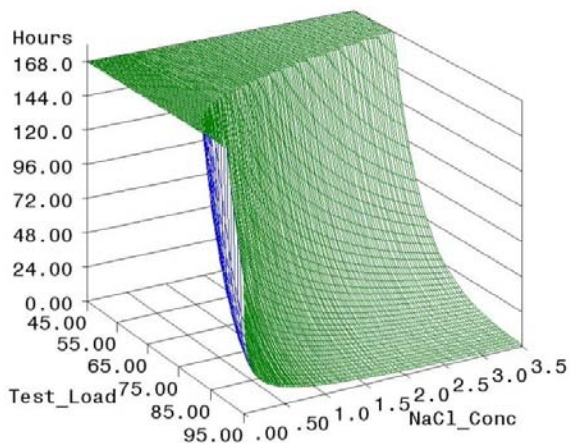
Air-melt (SAE-AMS-6415) to Aerospace (SAE-AMS-6414) Comparison

- Both demonstrate low susceptibility at or below T2 (158 ksi)
 - Even 168 hours in 3.5% NaCl not embrittling to T2 (158 ksi)
 - Environmental corrosion effects negligible below T2 (158 ksi)?
- Air-melt (lower strength at equivalent hardness) shows more tolerance
 - Not the “worst case” expected
 - Inclusions and defects absorb hydrogen
 - F519 changes needed? YES!
 - Air-melt difficult to obtain, limited use
 - Not used in aerospace
 - Doesn't put boundary on susceptibility as intended

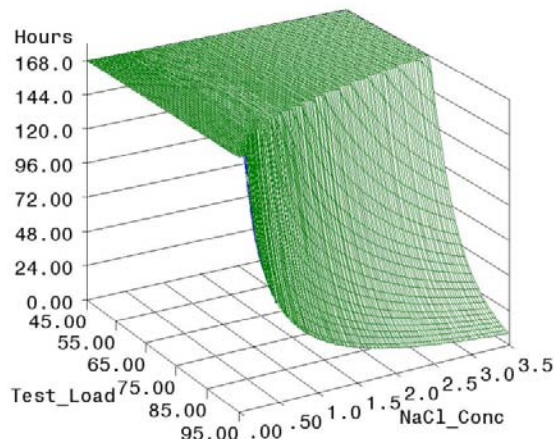
T3 Results-Aerospace 6414

Predicted Median Lifetime Strength=T3 (210 KSI) Predicted Median Lifetime Strength=T3 (210 KSI) Predicted Median Lifetime Strength=T3 (210 KSI)

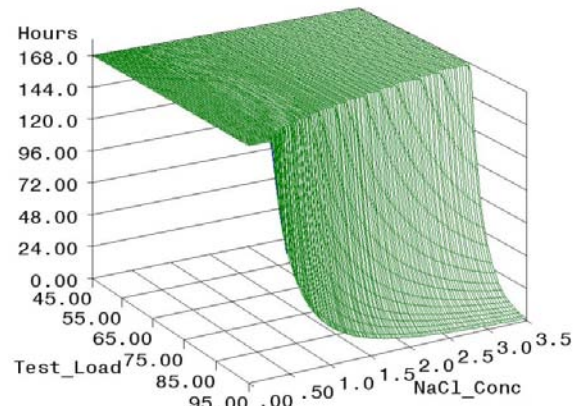
1a1



1a2

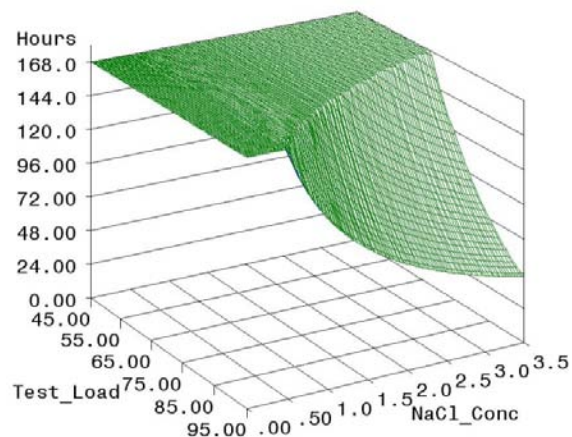


1d



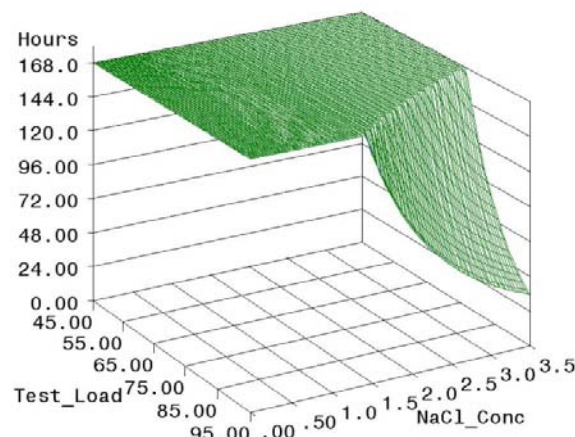
Predicted Median Lifetime Strength=T3 (210 KSI)

1c



Predicted Median Lifetime Strength=T3 (210 KSI)

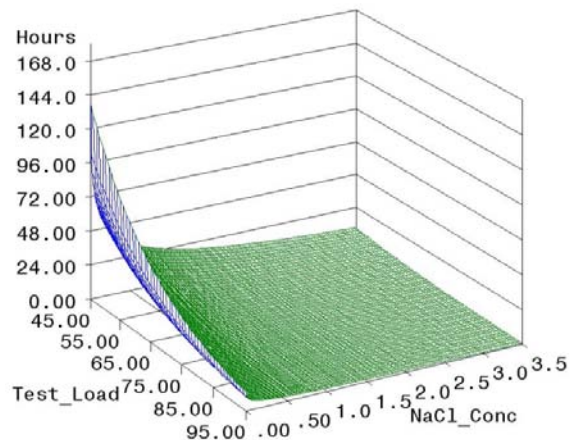
1e



T4 Results-Aerospace 6414

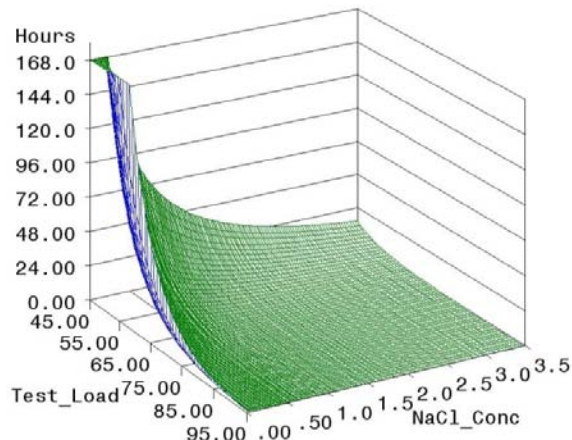
Predicted Median Lifetime
Strength=T4 (262 KSI)

1d



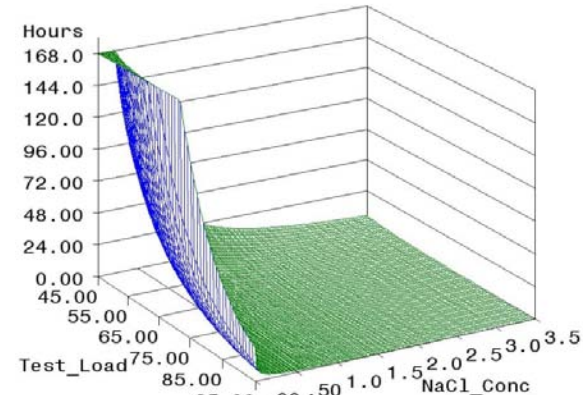
Predicted Median Lifetime
Strength=T4 (262 KSI)

1a1



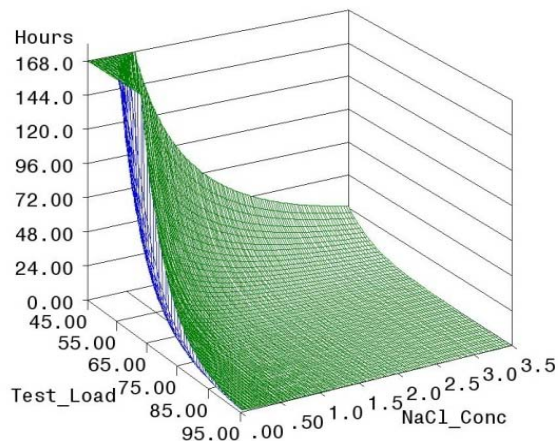
Predicted Median Lifetime
Strength=T4 (262 KSI)

1e



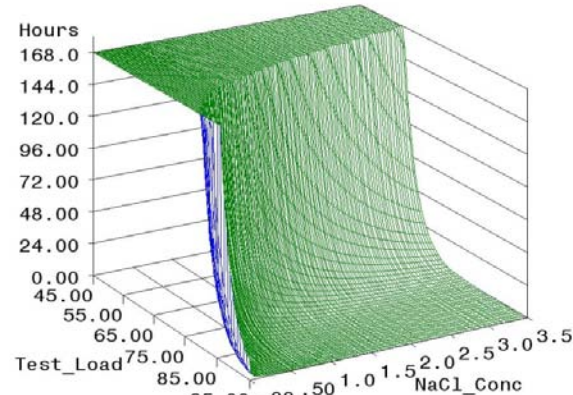
Predicted Median Lifetime
Strength=T4 (262 KSI)

1a2



Predicted Median Lifetime
Strength=T4 (262 KSI)

1c

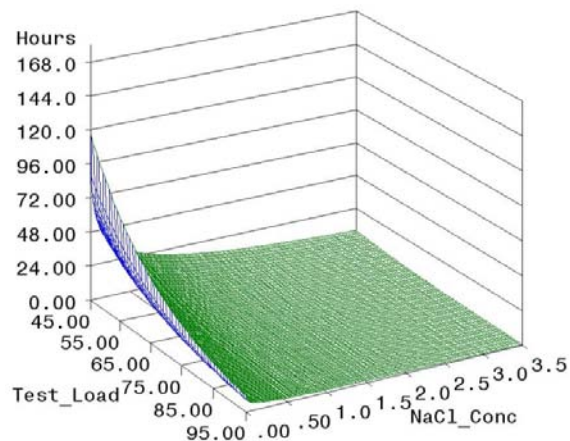


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T5 Results-Aerospace 6414

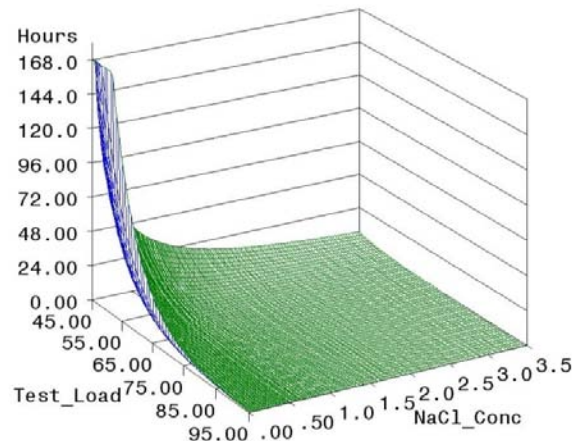
Predicted Median Lifetime
Strength=T5 (280 KSI)

1d



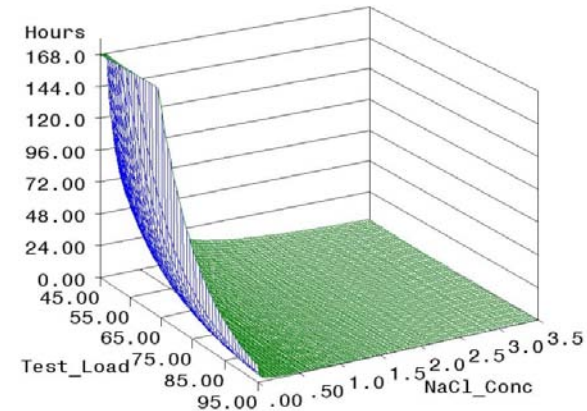
Predicted Median Lifetime
Strength=T5 (280 KSI)

1a1



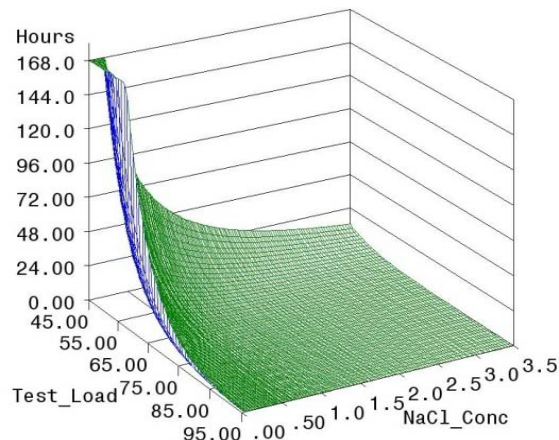
Predicted Median Lifetime
Strength=T5 (280 KSI)

1e



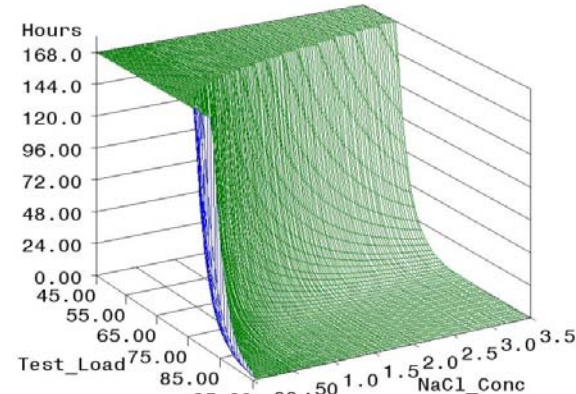
Predicted Median Lifetime
Strength=T5 (280 KSI)

1a2



Predicted Median Lifetime
Strength=T5 (280 KSI)

1c

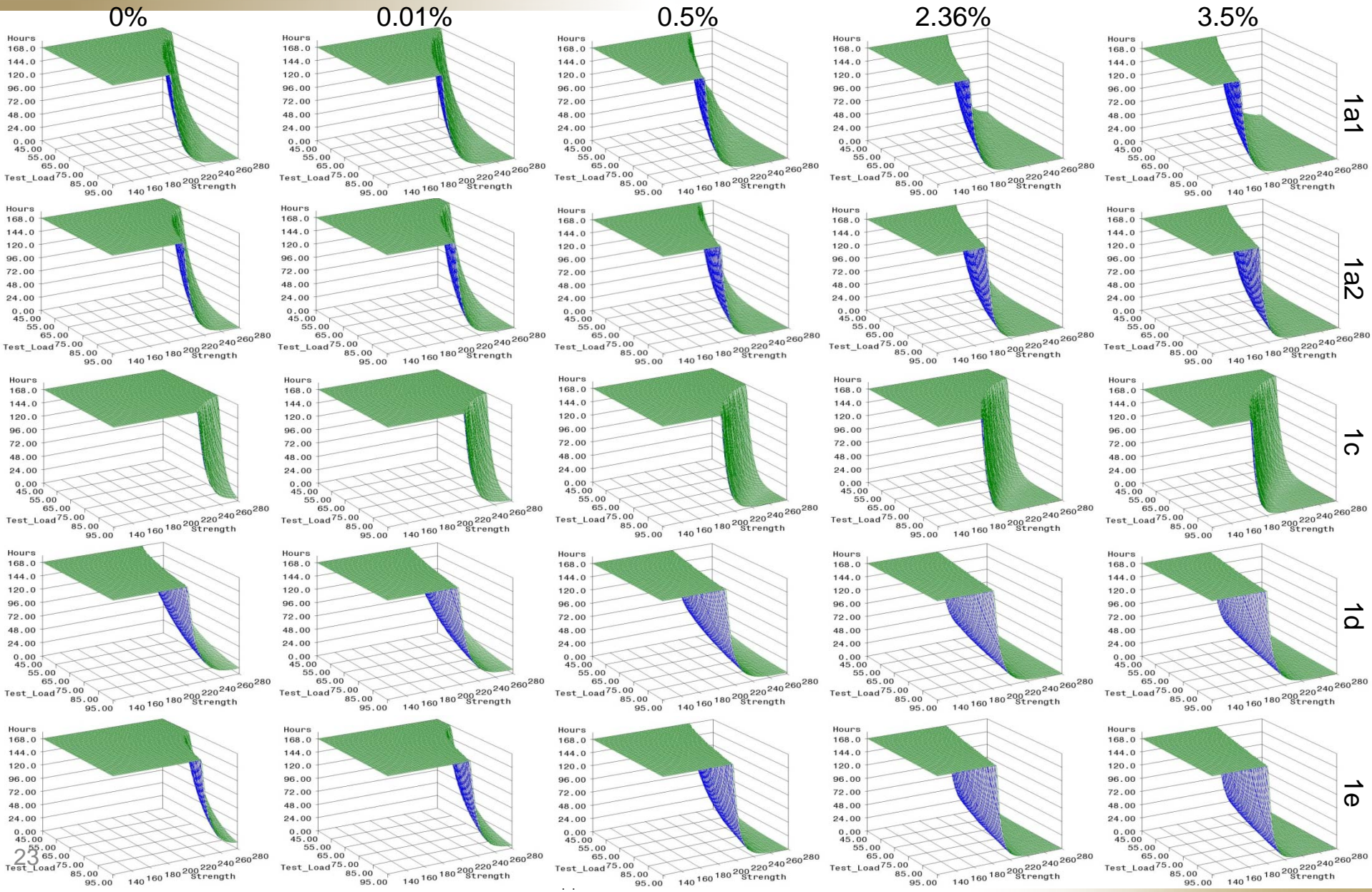


Geometry Comparison

- All show increased sensitivity with strength, applied load, NaCl conc. as expected
- 1d geometry shows most sensitivity, 1c least



Effect of %NaCl



- Assume %NaCl = amount of hydrogen, these 3d graphs correctly showing “cliff” behavior for the threshold
 - Once H₂ threshold is exceeded, specimens break
- Even residual stresses are high enough to cause susceptibility in steels approaching 250 ksi
- 1d most uniform performance?

Transition Plan

- Work has been briefed and discussed by ASTM committee F07 on Aerospace and Aircraft, and in detail within subcommittee .04 on hydrogen embrittlement
- Most active participants of the committee are directly involved
- Changes to F-519 are likely upon completion and data review
- Lifetime prediction models for the targeted maintenance chemicals will be utilized by aviation authorities to alleviate the presently existing bake relief requirement for processes that have failed HE testing
 - ◆ Material applications below susceptibility threshold (e.g. 180 ksi)
 - ◆ Service stress applications below threshold (e.g. below 50% UTS)
- Lifetime prediction models for cadmium alternatives will be transitioned to service use for applications shown to be below the HE susceptibility threshold (e.g. ZnNi 200 ksi steel)
- Commercial partners will follow guidance from the aviation authority in implementing targeted applications deemed safe.

Condition	- α	-	0	+	+ α
Strength (ksi)	210	220	245	270	280
Test Load (% NFS)	35	45	60	75	90
AQ Concentration	1.25E-05	4.5	17.3	30	34.5

- Run risk reduction +/- sigma to validate appropriate test loads
- Use 1d specimen type
- Linear, Quadratic, Confirmation Runs
- Base model is developed from Linear and Quadratic portions
 - $\ln X = 19.01 - 11.67 * \text{strength} - 9.93 * \text{test_load} - 0.88 * \text{NaCl} + \text{offset}$
 - Run confirmations, then re-compute, then refine model