

# *Development and qualification of S53 ultrahigh-strength corrosion resistant steel for cadmium replacement*

JCAT

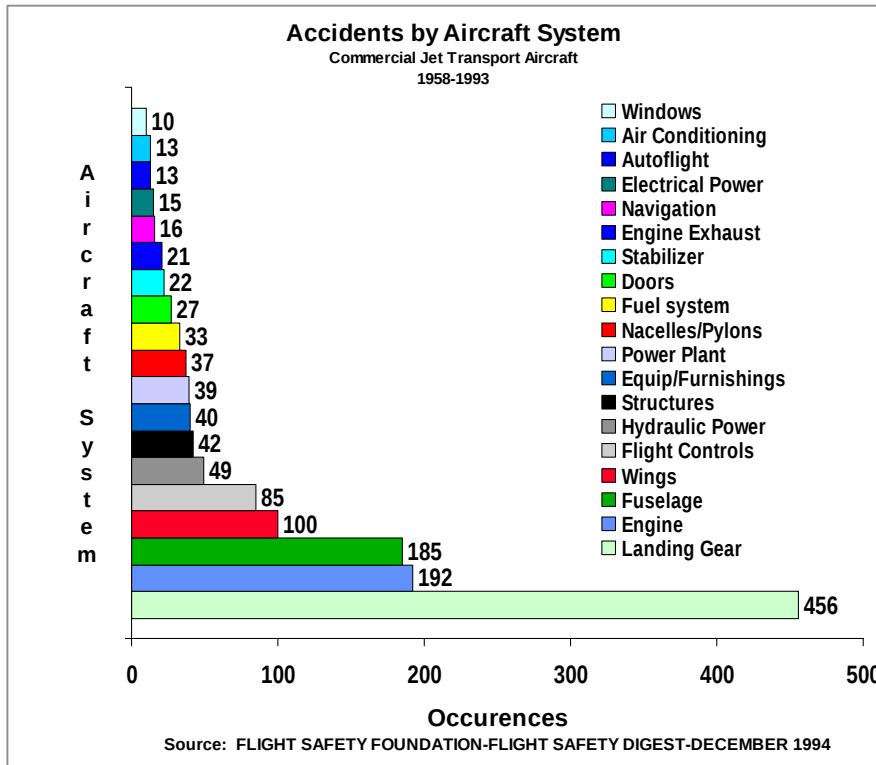
January 26, 2006 – San Diego, CA

Charlie Kuehmann



| Report Documentation Page                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |                                    |                                     |                                                                  | Form Approved<br>OMB No. 0704-0188                  |                                    |
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| 1. REPORT DATE<br><b>26 JAN 2006</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |                                    | 2. REPORT TYPE                      |                                                                  | 3. DATES COVERED<br><b>00-00-2006 to 00-00-2006</b> |                                    |
| 4. TITLE AND SUBTITLE<br><b>Development and qualification of S53 ultrahigh-strength corrosion resistant steel for cadmium replacement</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |                                    |                                     |                                                                  | 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)<br><b>QuesTek Innovations LLC,1820 Ridge Avenue,Evanston,IL,60201</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |                                    |                                     |                                                                  | 8. PERFORMING ORGANIZATION<br>REPORT NUMBER         |                                    |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |                                    |                                     |                                                                  | 10. SPONSOR/MONITOR'S ACRONYM(S)                    |                                    |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                                    |                                     |                                                                  | 11. SPONSOR/MONITOR'S REPORT<br>NUMBER(S)           |                                    |
| 12. DISTRIBUTION/AVAILABILITY STATEMENT<br><b>Approved for public release; distribution unlimited</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                                    |                                     |                                                                  |                                                     |                                    |
| 13. SUPPLEMENTARY NOTES<br><b>26th Replacement of Hard Chrome and Cadmium Plating Program Review Meeting, January 24-26, 2006, San Diego, CA. Sponsored by SERDP/ESTCP.</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |                                    |                                     |                                                                  |                                                     |                                    |
| 14. ABSTRACT                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                                    |                                     |                                                                  |                                                     |                                    |
| 15. SUBJECT TERMS                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |                                    |                                     |                                                                  |                                                     |                                    |
| 16. SECURITY CLASSIFICATION OF:                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                                    |                                     | 17. LIMITATION OF<br>ABSTRACT<br><b>Same as<br/>Report (SAR)</b> | 18. NUMBER<br>OF PAGES<br><b>28</b>                 | 19a. NAME OF<br>RESPONSIBLE PERSON |
| a. REPORT<br><b>unclassified</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | b. ABSTRACT<br><b>unclassified</b> | c. THIS PAGE<br><b>unclassified</b> |                                                                  |                                                     |                                    |

# Drivers



**SCC failure**



**HE failure**

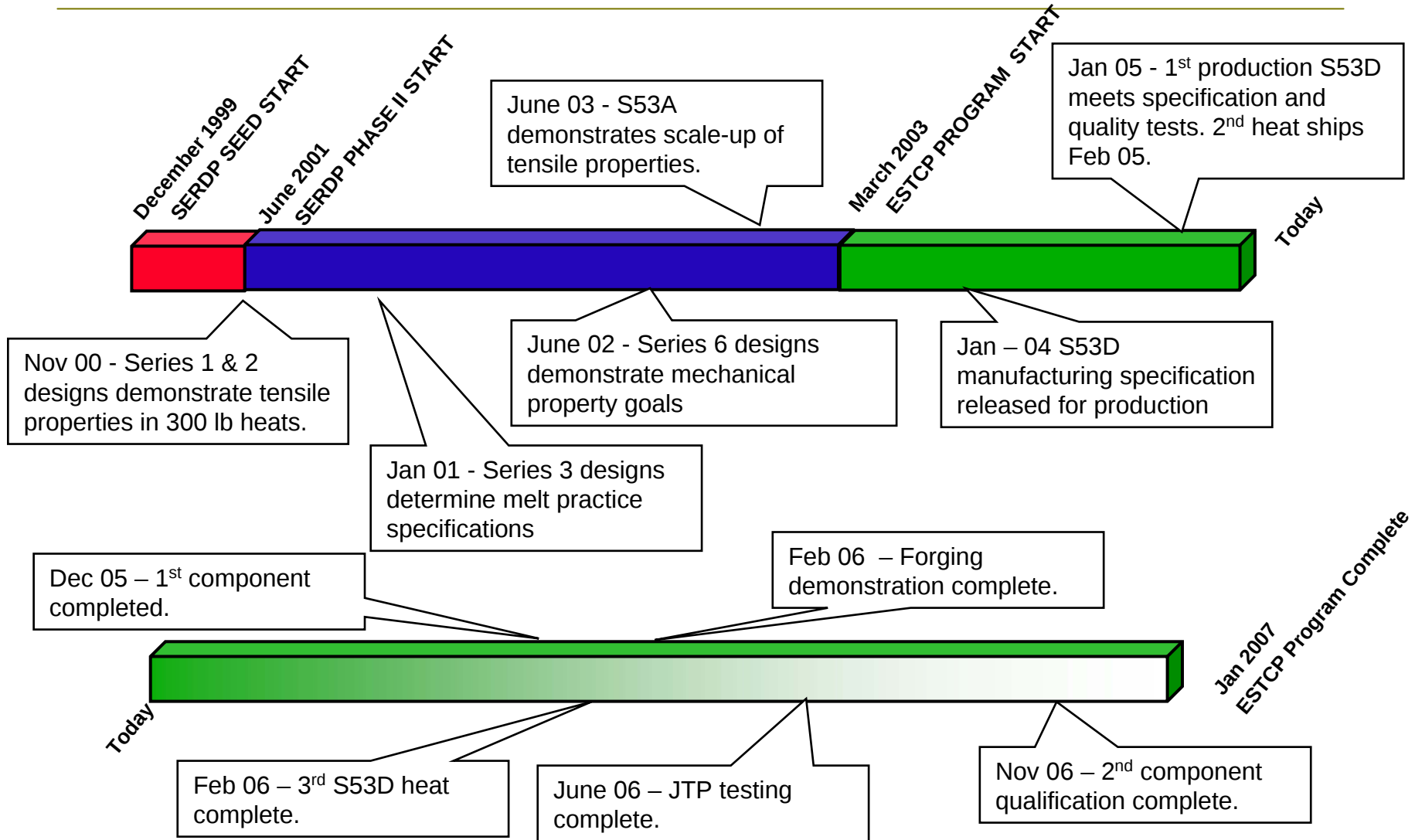
## Benefits:

- Dramatic reduction in LG cost (60%)
  - savings of \$120 million per year
- Significant reduction in SCC failures
- Cadmium plating not required
- General corrosion mitigated
- 80% of Steel Condemns Avoided

## Issues:

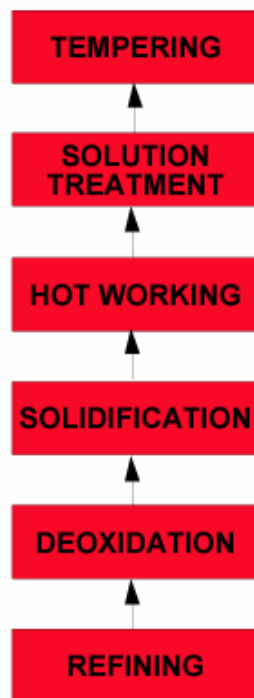
- Over \$200 million spent in LG per year
  - 80% corrosion related
- SCC failures
- Cad plating used to protect current steel known carcinogen (Hill AFB ~ 2000 lbs/yr)

# Milestones and Plans

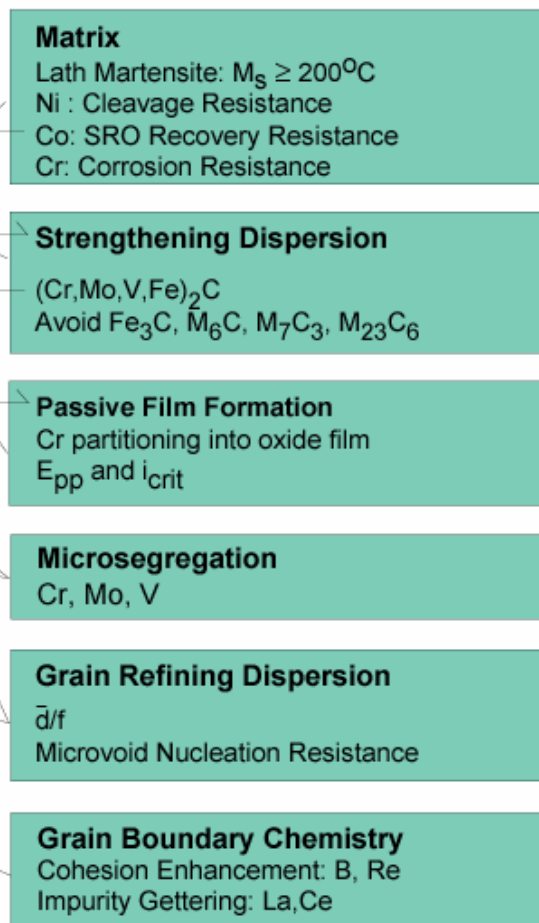


# S53 System Flow-Block Diagram

## PROCESSING



## STRUCTURE

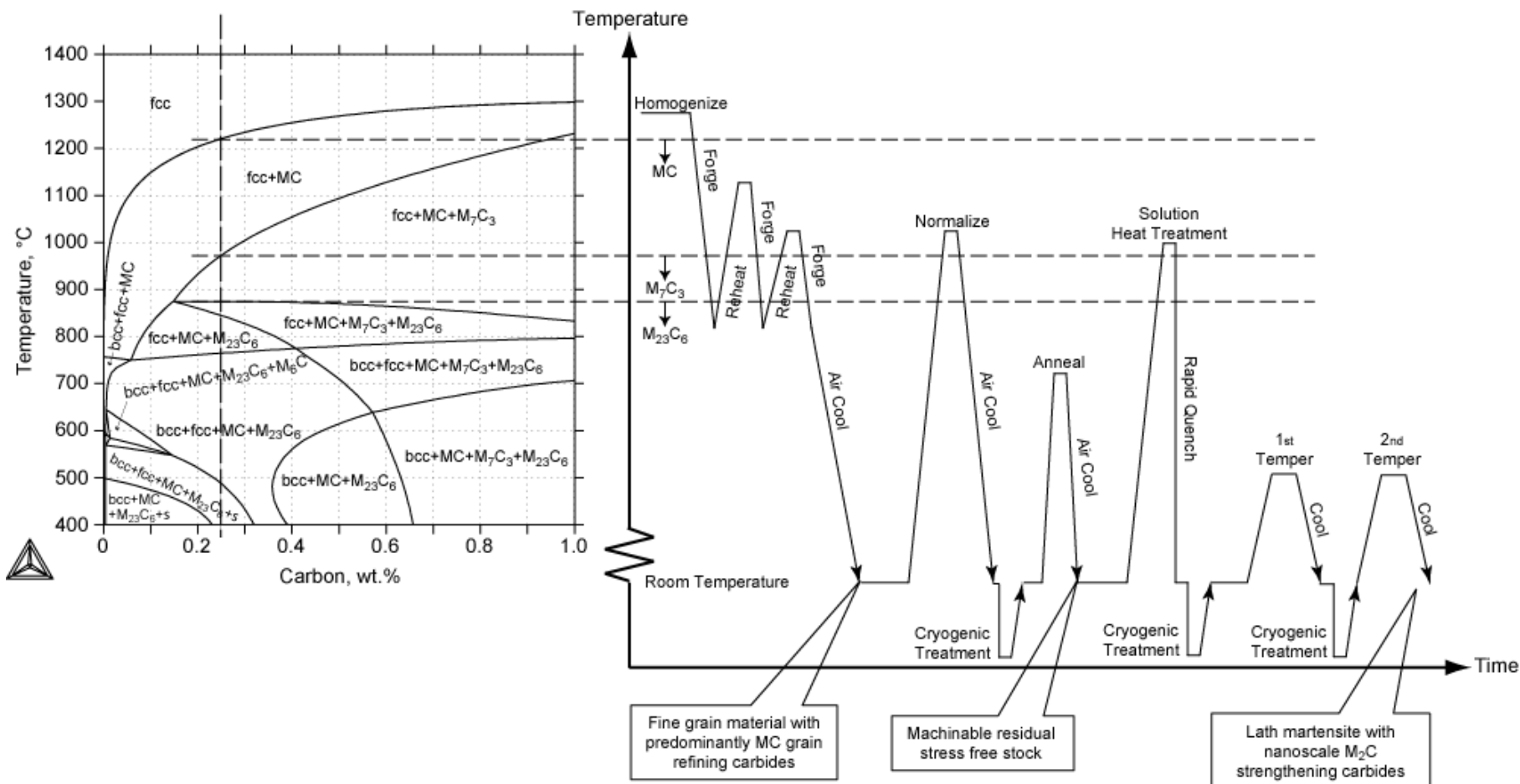


## PROPERTIES



## PERFORMANCE

# S53 Processing Schematic



# *ESTCP Program Objectives*

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- 3 Commercial scale heats
- Identify initial implementation components
- Qualification testing for AMS (S-basis) allowables
  - Execution of Joint Test Protocol (JTP)
  - Estimate MMPDS A & B-basis allowables by AIM
- Specifications for manufacturing process
  - Alloy Production
  - Forging
  - Rough Machining
  - Heat Treatment
  - Finish Machining/Surface Preparation
- Cost/Benefit Analysis
- Future Implementation Plan

# ESTCP Production Line-up

Primary VIM



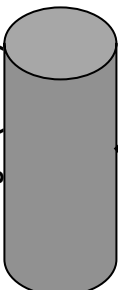
~ 20" Ingots (7 tons)



Secondary VAR – 24 in.



~ 24" Ingot (7 tons)



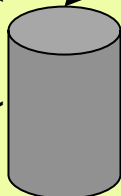
Homogenization



Press Forge



~ 16" DOC (2.5 tons)



Demo Plan

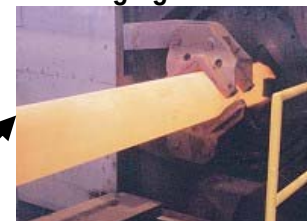
Bar Rolling



~ 8.5" RND (2500 lbs)



Bar Forging



JTP

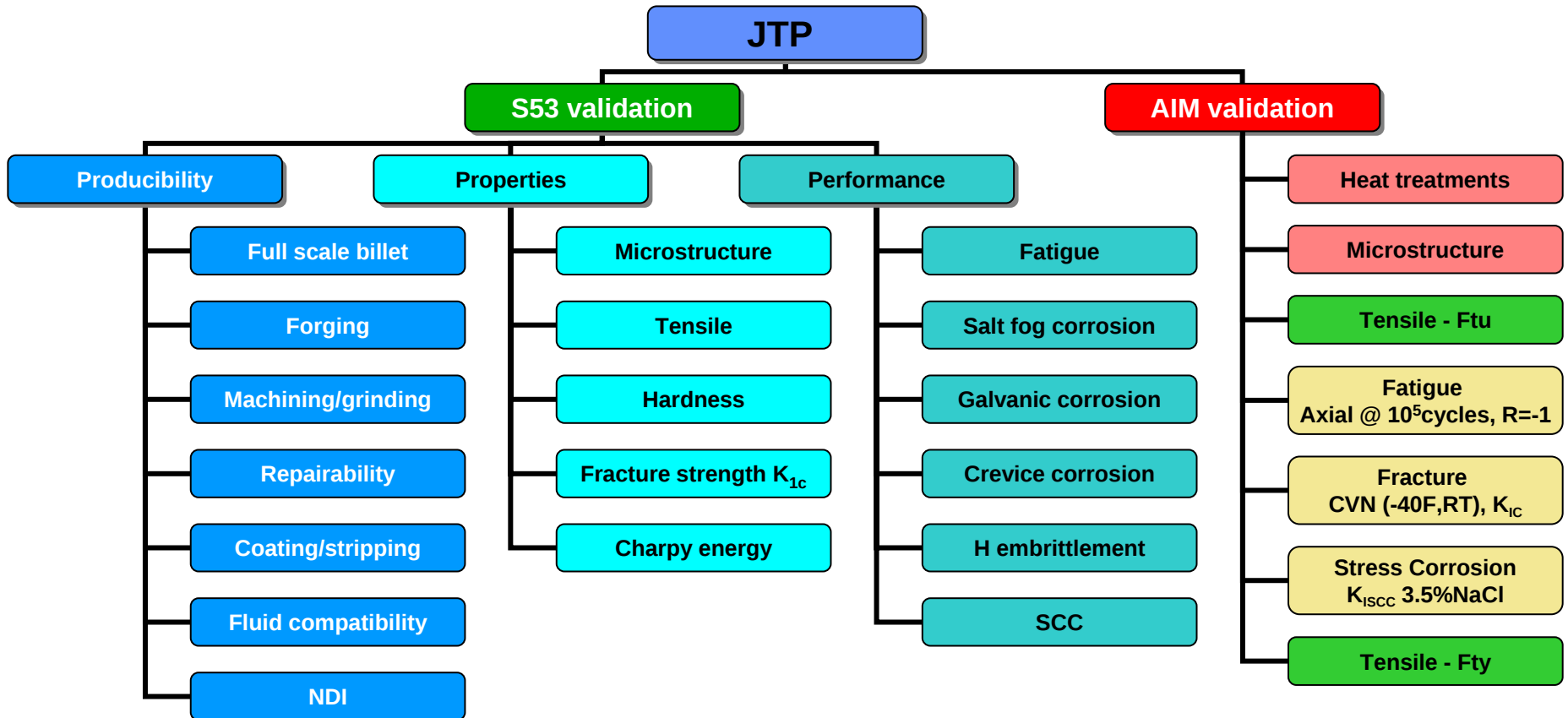
4" RCS (~2000 lbs)



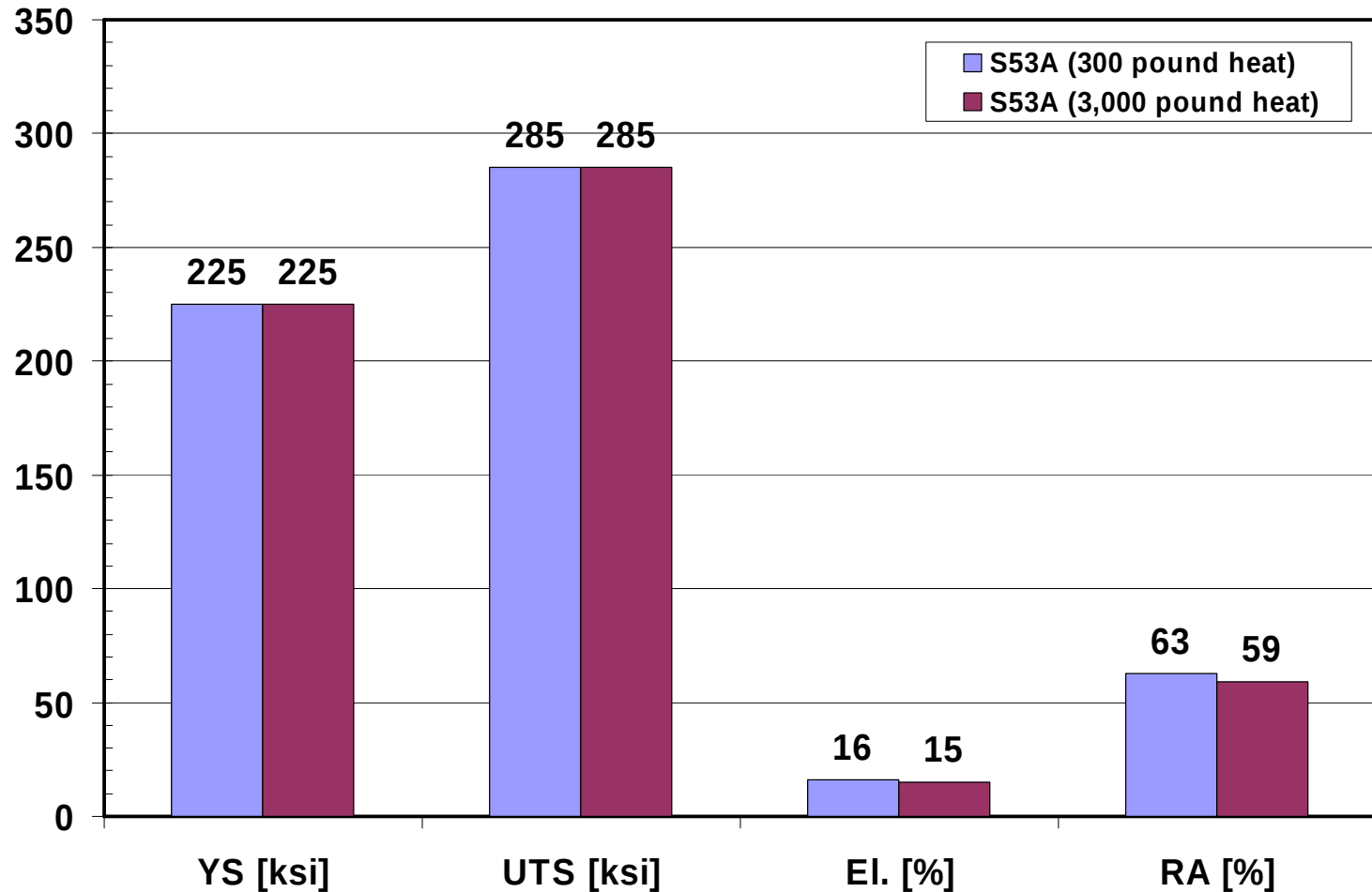
8" RND (~2000 lbs)



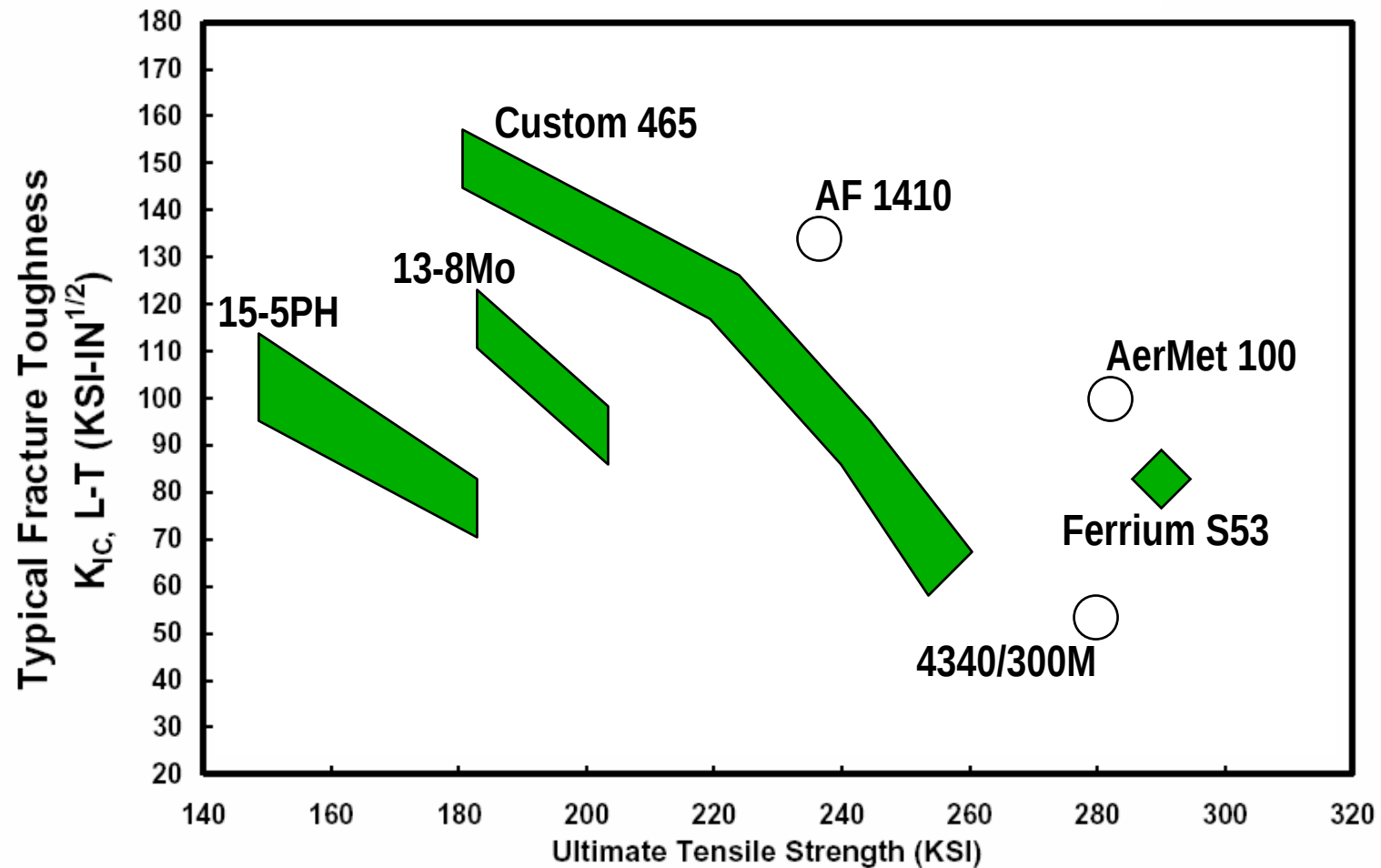
# Joint Test Protocol



# S53A Scale-up Properties



# S53 Nanostructured UHS Stainless Results



# Baseline Data

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## Ideal Heat Treatment Condition:

1100C 70 min + OQ + -78C 1 hr + AW(RT) + 505C 3 hrs + WQ

+ -78C 1 hr + AW(RT) + 492C 12 hrs + AC

### 209126

|          |              | 0.2% YS | UTS   | CVN | K <sub>IC</sub> |
|----------|--------------|---------|-------|-----|-----------------|
| 8" round | Longitudinal | 229.4   | 288.5 | 21  | 67              |
|          | Transverse   | 230.6   | 285.0 | 20  | 74              |
| 4" RCS   | Longitudinal | 229.8   | 285.3 | 19  |                 |

### 209193

|          |              |       |       |    |  |
|----------|--------------|-------|-------|----|--|
| 8" round | Longitudinal | 222.3 | 287   | 23 |  |
| 4" RCS   | Longitudinal | 223.7 | 287.2 | 24 |  |

# Heat Treatment Conclusions

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- Cryo not necessary to go all the way to liquid nitrogen

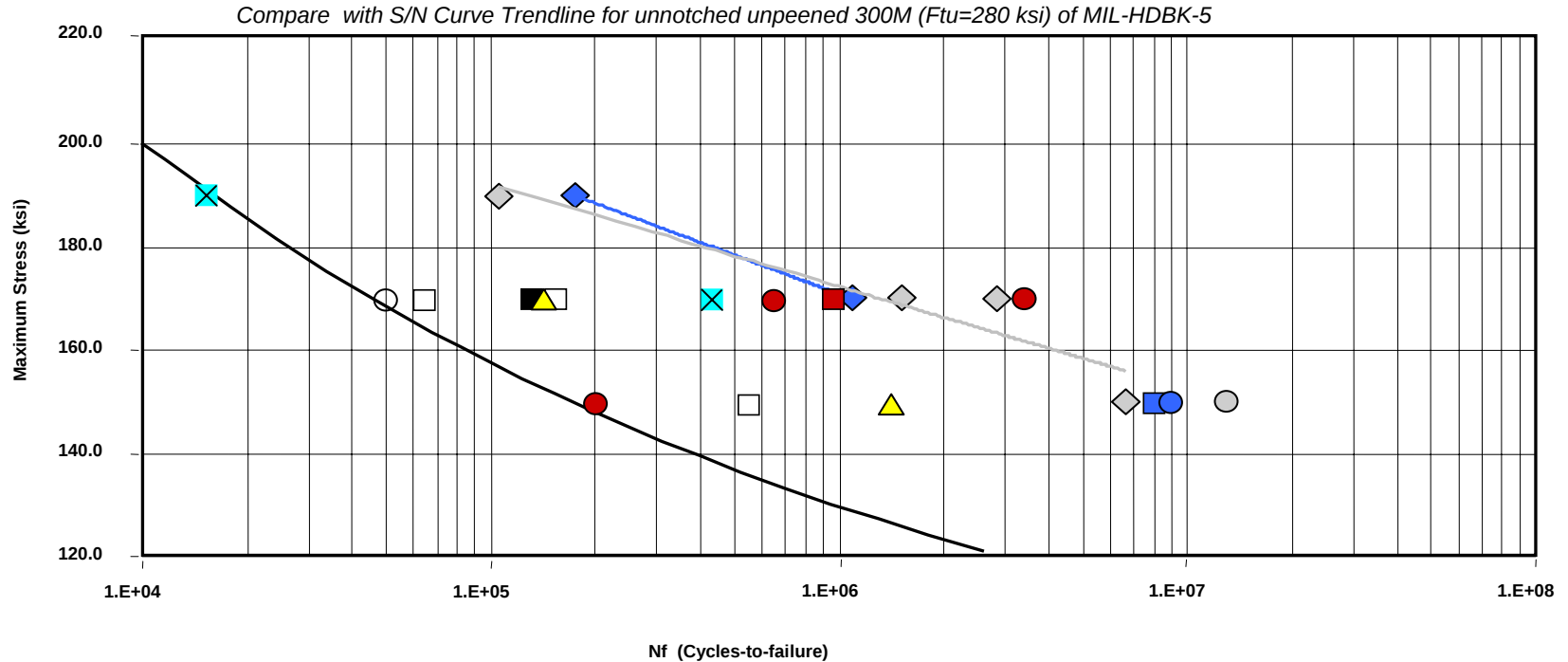
|       | 0.2% YS | UTS   | CVN |
|-------|---------|-------|-----|
| -78C  | 229.4   | 288.5 | 21  |
| -196C | 227.1   | 288.1 | 21  |

- Up to 8 hours after quench is acceptable before cryo-treatment

|          | 0.2% YS | UTS   | CVN |
|----------|---------|-------|-----|
| 1 hour   | 225.1   | 287.9 | 22  |
| 5 hours  | 221.6   | 289.1 | 22  |
| 8 hours  | 231.3   | 284.4 | 20  |
| 24 hours | 214.7   | 285.4 | 23  |

**Successful scale-up: Fatigue of Production S53 alloy product forms from large Heat meet or exceed the 300M alloy fatigue trendline (L & T) of MIL-HDBK-5, and Longitudinal data matches L data of SERDP program's S53 alloy R&D small Heat**

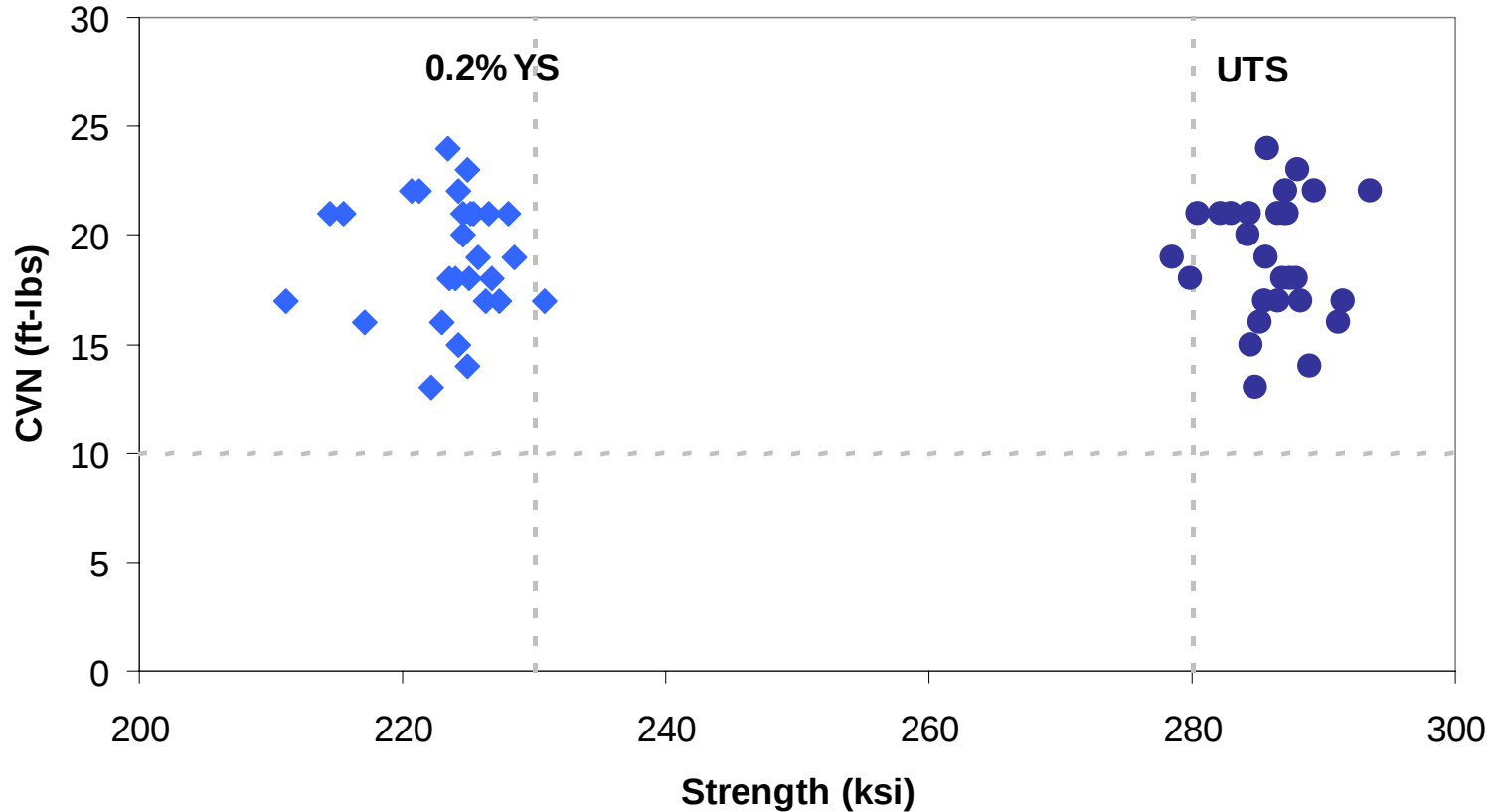
ESTCP Program on Ferrium S53 Corrosion Resistant Steel:  $R = -0.33$  Fatigue Data: for 300M ( $S_u = 284$  ksi) & S53-6F ( $S_u = 291$  ksi) (from 300 lbs Heat) of SERDP/2003 and production grade S53 ( $S_u = 284$  ksi) (from 10,000 lbs Heats).



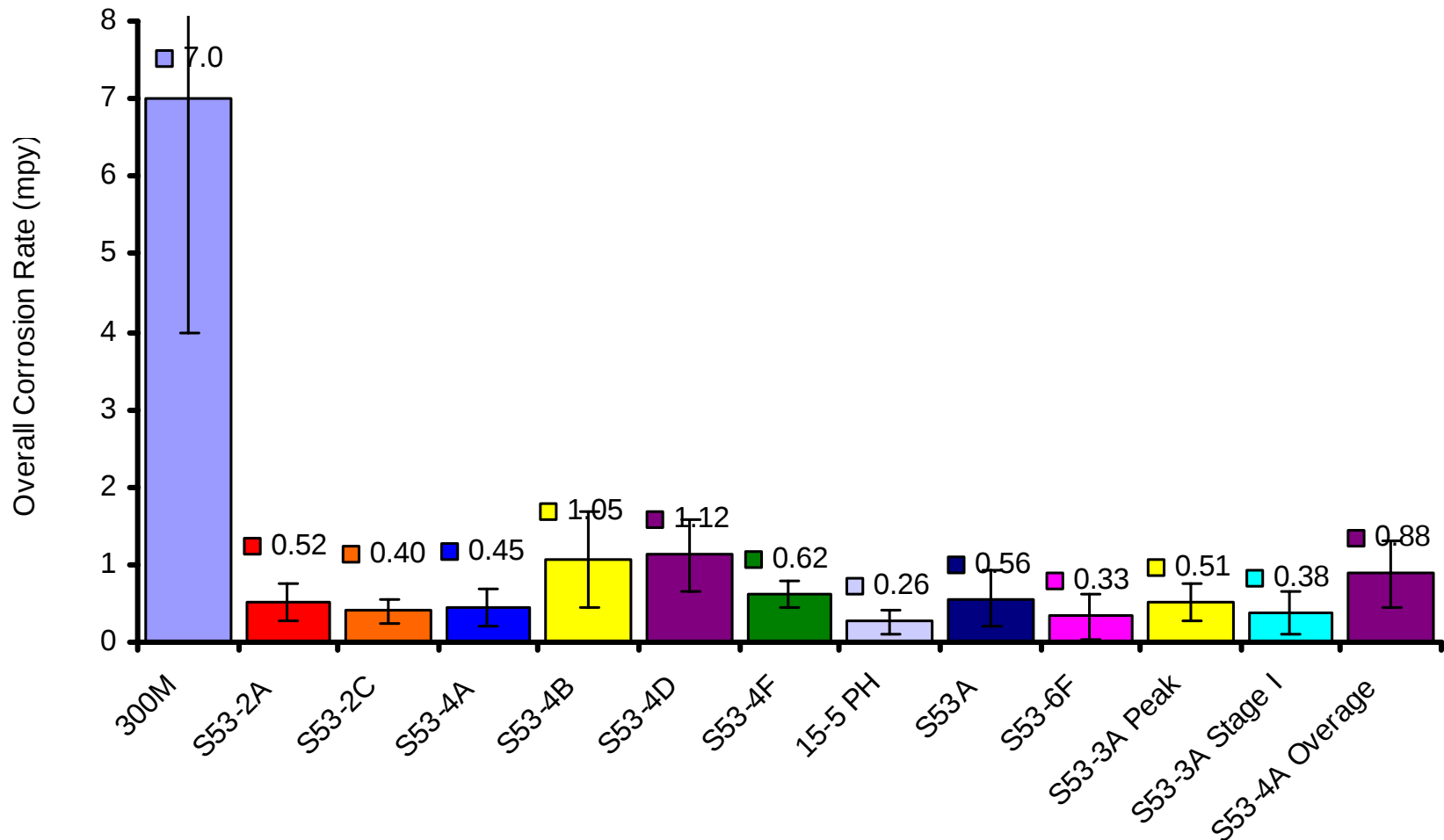
- |                                      |                                                 |                                          |
|--------------------------------------|-------------------------------------------------|------------------------------------------|
| — MIL-HDBK- 5; $R = -0.33$ Trendline | ✕ L- 300M unpeened, polished; different lot (E) | ○ T – 8" $\Phi$ bar HT# 1; 1" re-HT# 3   |
| ◆ L- 300M peened                     | ◇ L- Ferrium S53-6F peened                      | ■ L – 4"RCS bar HT# 1; 1" re-HT# 3       |
| ■ L- 300M peened; discontinued       | ○ L- Ferrium S53-6F unpeened; discontinued      | □ T – 4"RCS bar HT# 1; 1" re-HT# 3       |
| ● L- 300M unpeened; discontinued     | — Ferrium S53-6F peened                         | ■ T – 0.75" x 4"RCS bar; HT# 1           |
| — 300M peened                        | ● L – 8" $\Phi$ bar HT# 1; 1" re-HT# 3          | ▲ T – 0.86" t x 5" $\Phi$ die-fg.; HT# 2 |

## Sensitivity Analysis

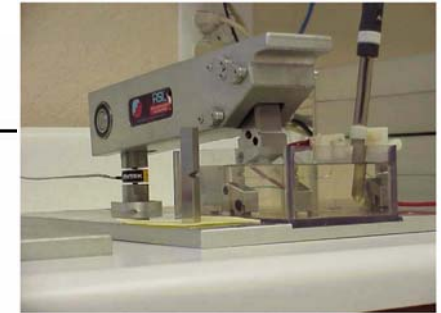
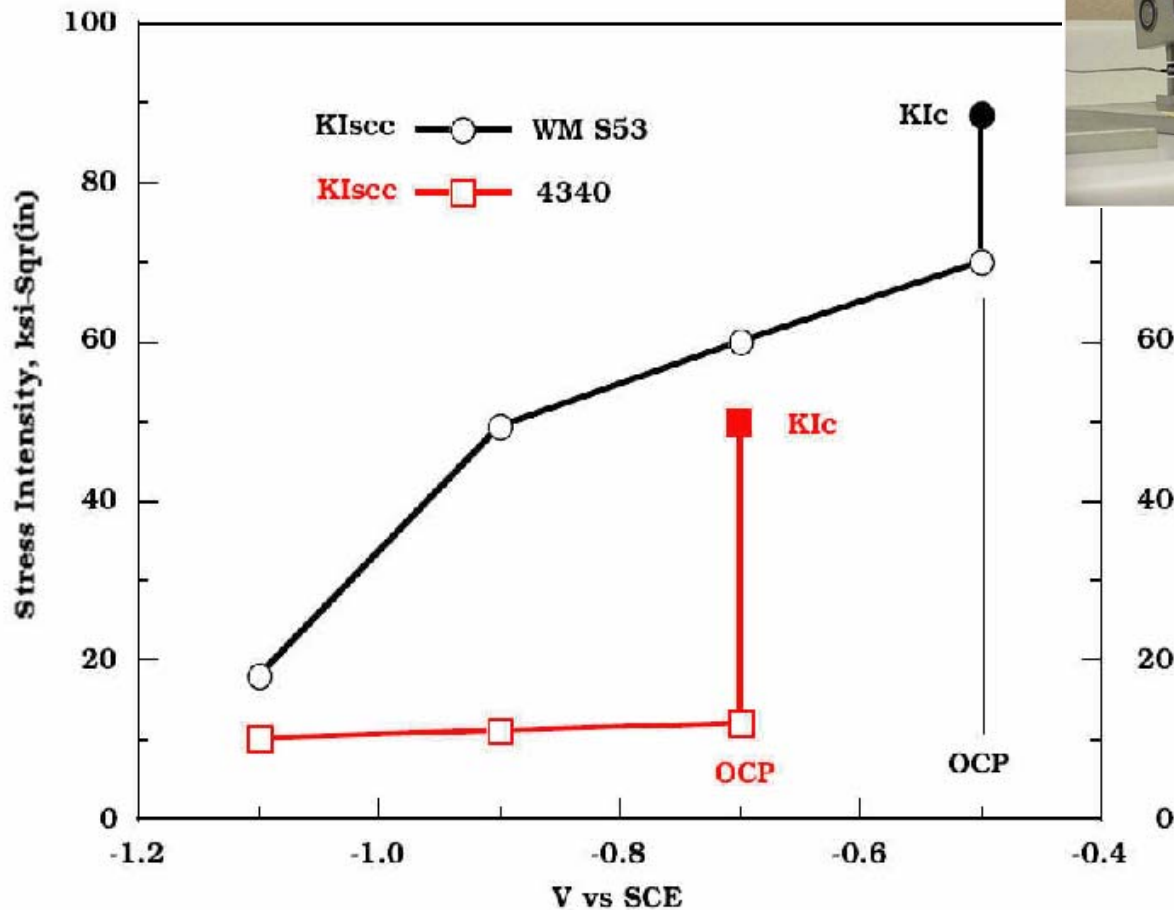
- +/- 7C in temperature (solution and tempering)
- +/- 30 minutes in time (solution and tempering)
- Represents 28 samples



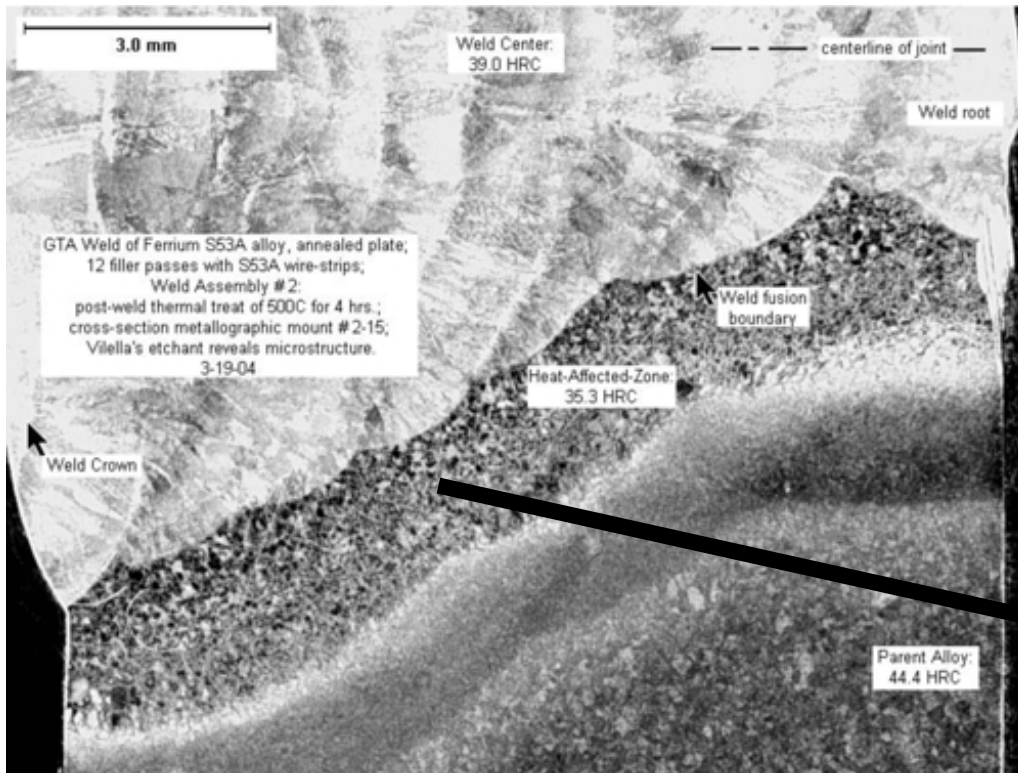
# Corrosion Results from Anodic Polarization



# $K_{ISCC}$ Results of Ferrium™ S53 vs 4340

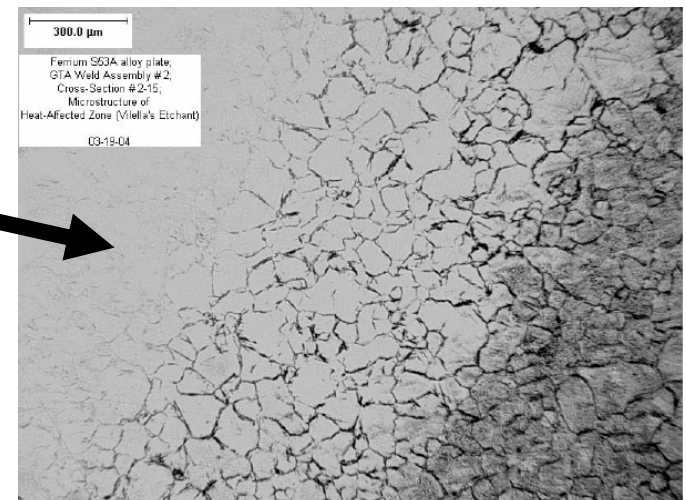


# Weld Microstructure & Mechanical Properties



|                      | Base Metal | Weld Metal |
|----------------------|------------|------------|
| <b>UTS (ksi)</b>     | 276        | 275        |
| <b>YS (ksi)</b>      | 226        | 220        |
| <b>Elong.%</b>       | 15         | 9          |
| <b>CVN (ft-lbs.)</b> | 7          | 6          |

Study completed on S53A heat HC56 rejected for high N content.



# Annealed S53 Machinability Evaluations

- Turning annealed Ferrium S53 at 38 to 40 HRC is harder than turning 300M and AerMet 100 in the normalized and annealed condition.
- Ferrium S53 hardens during turning inducing an unusual wear of the inserts.
- Lower speed is needed to have a reasonable inserts wear.
- A very important deformation (TIR) was noted on a 7.75" bar (0.040"), even with a low speed, which is not acceptable.
- Feed is found to be the most critical parameter to decrease the deformation (TIR) of the bars. Feeds as low as 0.006" are needed (compared with 0.012" for Aermet 100).
- Very good finishes after turning could be reached (34 Ra) with the most performing inserts.
- S53D Spec. incorporates a cryo treatment to address high annealed hardness and high work hardening rate – initial results are positive.



(a) cutting



(b) mill facing



(c) rounded end milling



(d) center drilling

| P/N     | Dimension           | Number of parts | Interrupted turning | Continuous turning | Drilling | Tapping |
|---------|---------------------|-----------------|---------------------|--------------------|----------|---------|
| SK-0110 | 3.5" x 3.5" x 7.75" | 6               | √                   | √                  |          |         |
| SK-0112 | 3.5" x 3.5" x 7.75" | 5               | √                   | √                  |          |         |
| SK-0113 | 3.5" x 3.5" x 23"   | 1               | √                   | √                  |          |         |
| SK-0114 | 3.5" x 3.5" x 7.75" | 2               | √                   | √                  |          |         |
| SK-0115 | 3.5" x 3.5" x 7.75" | 2               | √                   | √                  |          |         |
| SK-0116 | 3.5" x 3.5" x 17.3" | 1               |                     |                    | √        | √       |
| SK-0117 | 0.7" x 6" x 24"     | 2               |                     |                    | √        |         |

# *Production S53 Annealed Machinability*

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ESTCP Program on S53 Alloy;  
GA Drawing # 15 - Machineability Test Article:  
S53 alloy, condition N + CRYO + ANN by CarTech; 35HRC  
Production Heat # 209126



ESTCP Program on S53 Alloy;  
GA Drawing # 15 - Machineability Test Article:  
S53 alloy, condition N + CRYO + ANN by CarTech; 35HRC  
Production Heat # 209126



# S53 Fully Hardened Machining Evaluations

Threaded S53 sample piece



| P/N – Dia (inch) | Number of parts | Turning                                    | Threading | Drilling |
|------------------|-----------------|--------------------------------------------|-----------|----------|
| SK-0110 – 1.50   | 6               | √ (parts prepared for the grinding trials) |           |          |
| SK-0111 – 1.75   | 1               | √                                          |           |          |
| SK-0112 – 3.00   | 5               | √                                          |           |          |
| SK-0113 – 3.00   | 1               | √                                          |           |          |
| SK-0114          | 2, three diam   |                                            | √         |          |
| SK-0115 – 3.80   | 2               | √                                          |           |          |
| SK-0117 – plate  | 2               |                                            |           | √        |

| Alloy       | Insert            | Speed (SFM) (1) | Infeed (Inch per Revolution) | Depth of cut (inch) | BNI/Finish (2) |
|-------------|-------------------|-----------------|------------------------------|---------------------|----------------|
| 300M        | Carbide KC5010    | 160R            | 0.010                        | 0.075               |                |
|             |                   | 180F            | 0.008                        | 0.030               |                |
|             | Ceramics          | 550R/F          | 0.006                        | 0.030               |                |
| Aermet 100  | Carbide           | N/A             | N/A                          | N/A                 |                |
|             |                   | 160F            | 0.010                        | 0.010               |                |
| Ferrium S53 | Carbide           | 150R            | 0.008                        | 0.060               |                |
|             | KC5010/positive   |                 |                              |                     |                |
|             | Carbide           | 180F            | 0.008                        | 0.015               | A/58-64Ra      |
|             | KC7310/positive   |                 |                              |                     |                |
|             | Carbide KC5010 OR | 120F            | 0.008                        | 0.005               | A/55-71Ra      |
|             | EH510Z/positive   |                 |                              |                     |                |
|             | Carbide           | 90F             | 0.006                        | 0.015               | A/15-16Ra      |
|             | KC5010/positive   |                 |                              |                     |                |

## Grinding Results

- S53 is very difficult induce grind damage
- Grind burns could not be detected with a standard nital etch
- New etchant needs to be developed

# Forging Study

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A10 MLG Piston

Kropp Forge

5/17/05

Takeaways:

- Forges easily
- Forges better than AerMet
- Minimal (if any) change in mechanical properties



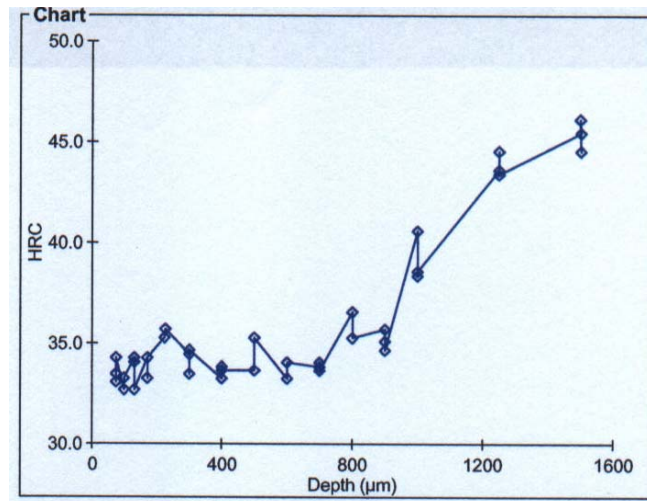
# A10 Forging Characterization

- Mechanical

(Longitudinal Orientation)

|              | 0.2% YS | UTS   | CVN |
|--------------|---------|-------|-----|
| 8" Bar Stock | 229.4   | 288.5 | 21  |
| A10 Forging  | 233.7   | 284.2 | 18  |

- Decarb



Decarb approximately 0.060" (1500 μm)

# Demonstration Target Components

A-10 Main Landing Gear



- A-10 main landing gear piston (4330 – 240 ksi)
  - More complex loading
  - Forged component
  - Currently in production for spares

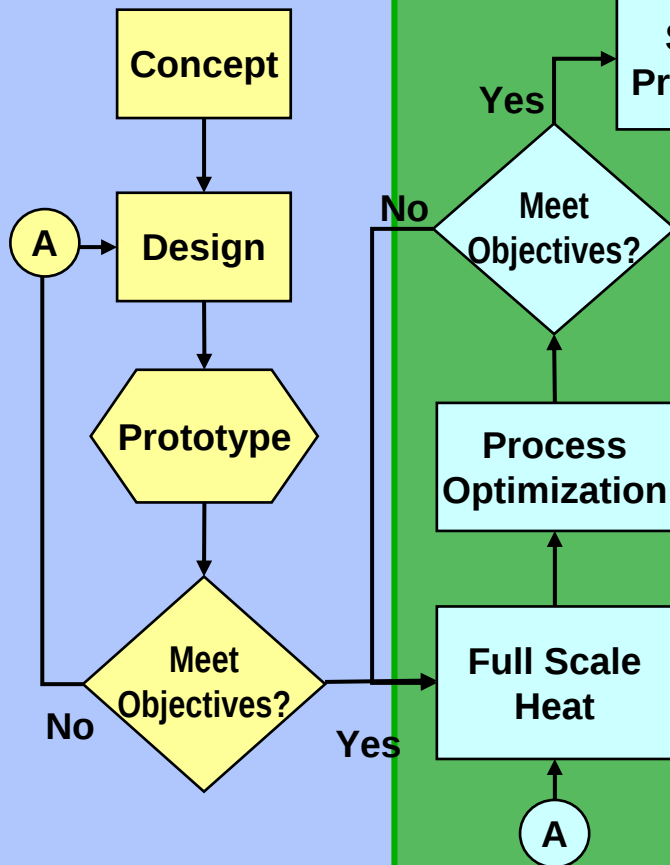
A-10 Nose Gear



- A-10 drag brace (300M - 270 ksi)
  - Simple tension loading
  - No forging required
  - Corrosion related failures

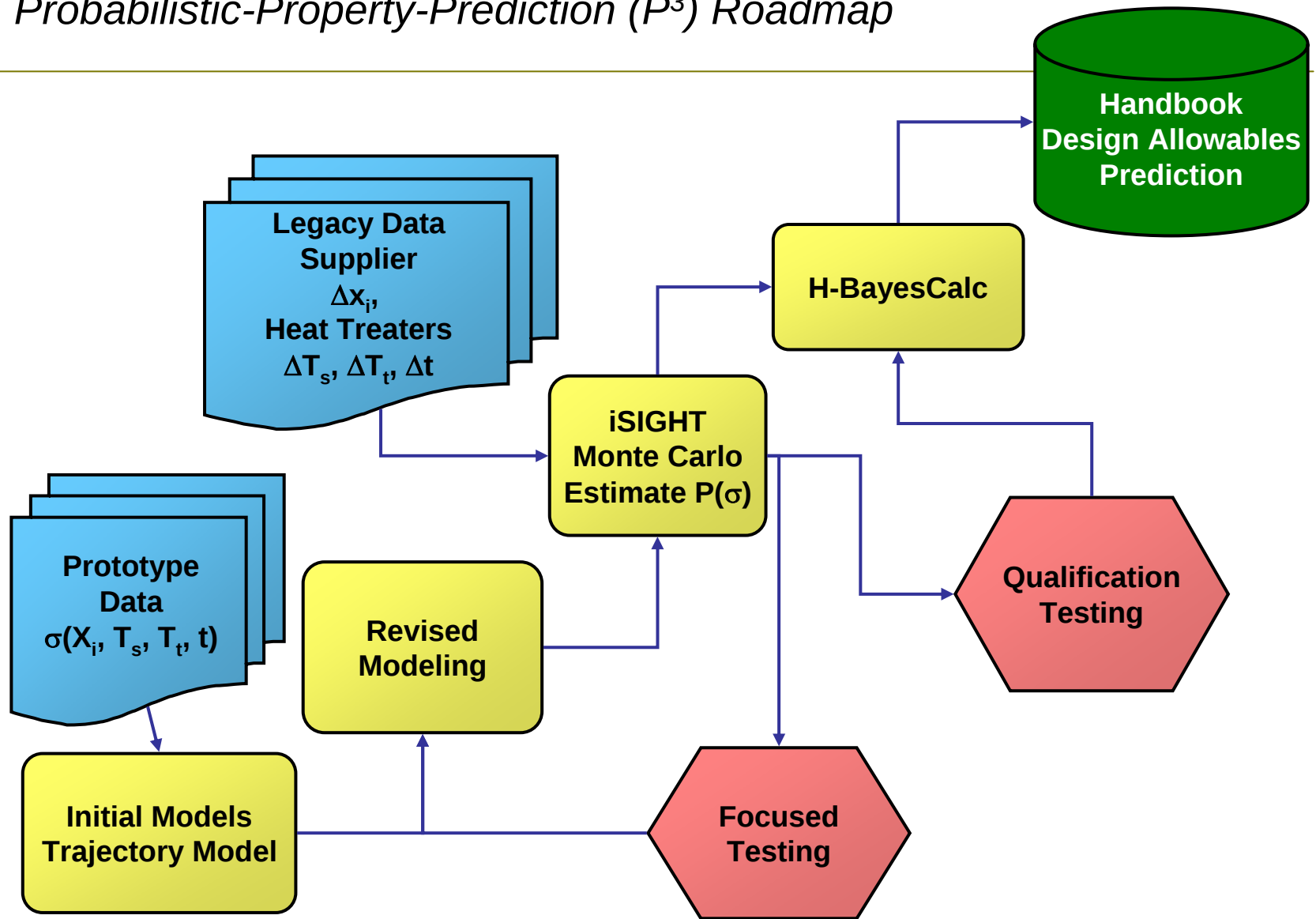
# Accelerating the Materials Development Cycle

## Materials by Design™



## AIM Methodologies

# Probabilistic-Property-Prediction ( $P^3$ ) Roadmap



# S53 Robust/Sensitivity Analysis with Compositional Variations

## Compositional Variations

(wt%,  $\pm 6\sigma$ ):

|                     |                     |                     |
|---------------------|---------------------|---------------------|
| <b>C</b> $\pm 0.01$ | <b>Cr</b> $\pm 0.2$ | <b>Mo</b> $\pm 0.1$ |
| <b>W</b> $\pm 0.1$  | <b>Co</b> $\pm 0.3$ | <b>Ni</b> $\pm 0.1$ |
| <b>V</b> $\pm 0.02$ |                     |                     |

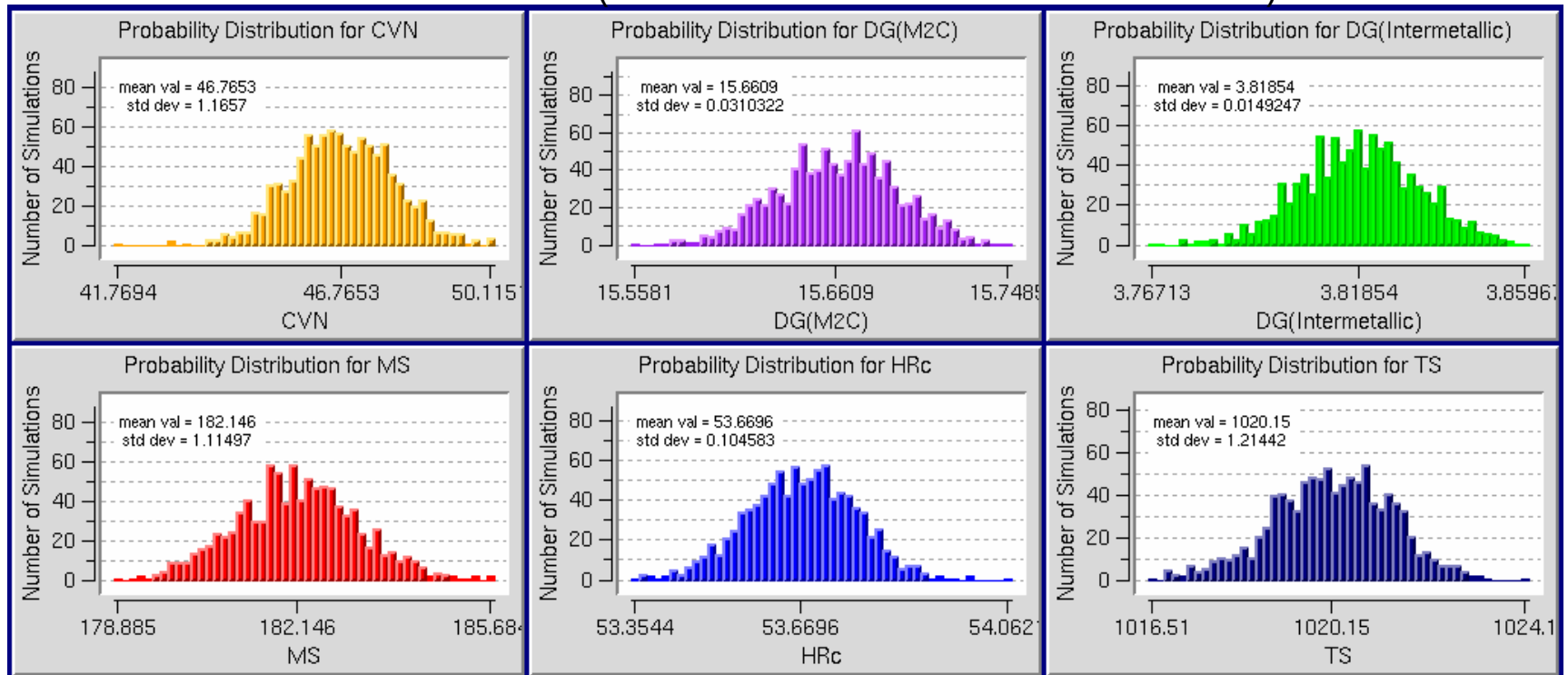
CMD/  
iSIGHT

## Variations of:

**Structure** — carbide solvus Ts, martensite Ms, precipitation control  $\Delta G$ 's

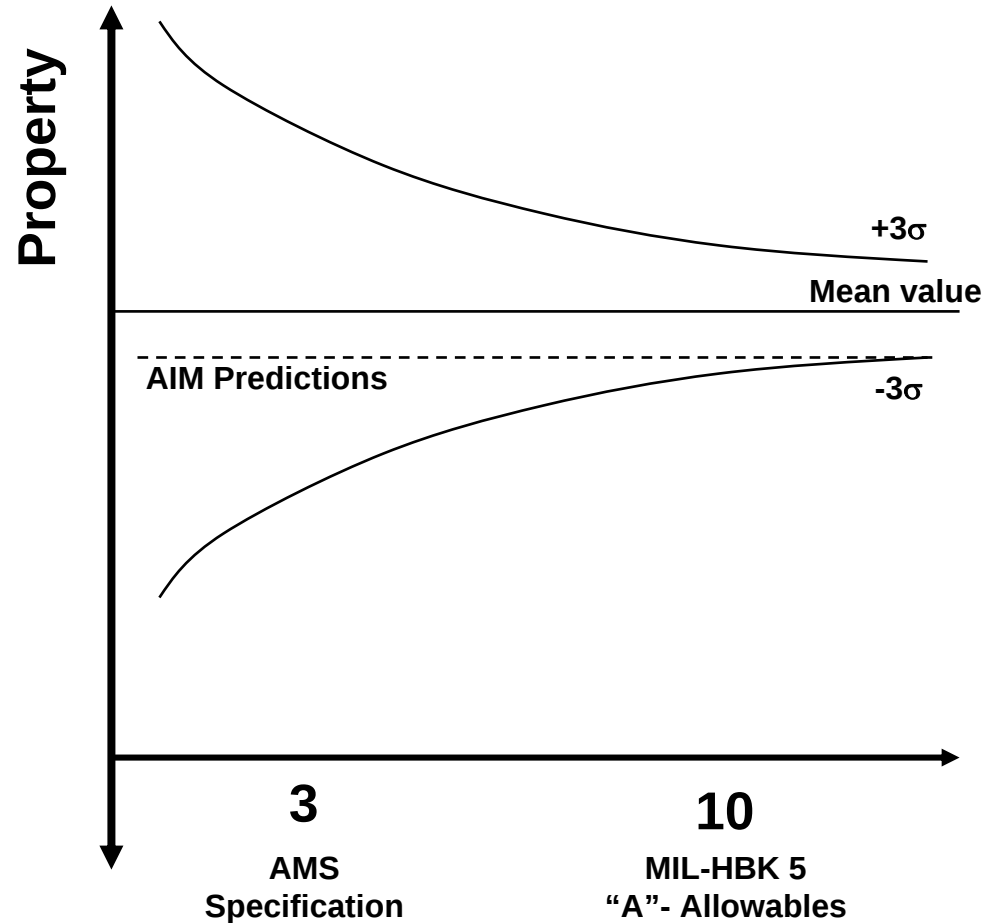
**Property** — hardness HRc, toughness CVN

Results of 1000 runs (12 minutes on a Pentium IV 2.2GHz CPU)



# ESTCP AIM Objectives

- Objective is to predict MIL-HBK 5 “A”- Allowables with only 3 heats available.
- Designers can design new LG components with confidence 3-5 years earlier.
- Testing costs are 70% lower, overall costs are 50% lower.



# Summary and Takeaways

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- S53 has demonstrated property goals in multiple production scale heats.
- Primary manufacturing evaluations have been completed for machining, surface treatments, and welding.
- Yield stress is the property most sensitive to process variation.
- AIM methods will predict MMPDS (MIL-HNBK-5) A-allowables with 3 heats completed.
- First applications to be completed for Air Force replacement requirements. A-10, 2007-2008

