New Ultra High Performance 
Ferrrium® Steels For Demanding 
Energy and Oil & Gas Applications
QuesTek Presentation Overview

1. Introduction to QuesTek

2. New High Performance Double Vacuum Melted VIM/VAR Steels, Commercially-Available from Carpenter Technology:
   - *Ferrium*® M54™ Alloy: Highly SCC resistant, higher strength and toughness upgrade from 4340 & Maraging Steels
   - *Ferrium*® S53® Alloy: Corrosion-Resistant upgrade from 4340 & Maraging Steels
   - *Ferrium*® C61™ & C64™ Alloys: Upgrades from 9310/EN36 and 8620

3. Example Materials Under Development
   - *Ferrium*® PH48S™ Castable Stainless Steel
   - *Ferrium* N63 Stainless Bearing Steel
   - Be-free High Strength Alternative Alloys
Background - QuesTek Innovations LLC

• A global leader in integrated computational materials design:
  – Our *Materials by Design*® technology and expertise applies Integrated Computational Materials Engineering (ICME) tools and methods to design improved alloys faster and at 70% less cost than traditional empirical methods

• Four computationally-designed, commercially-sold high performance steels

• Specialty alloys for government and industry

<table>
<thead>
<tr>
<th>Element</th>
<th>Atomic Number</th>
<th>Atomic Mass</th>
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<tbody>
<tr>
<td>Al</td>
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<td>26.982</td>
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<tr>
<td>Ti</td>
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<td>47.867</td>
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<tr>
<td>Fe</td>
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<td>55.845</td>
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<tr>
<td>Co</td>
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<td>Ni</td>
<td>28</td>
<td>58.693</td>
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<td>Cu</td>
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<td>63.546</td>
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<td>Nb</td>
<td>41</td>
<td>92.906</td>
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<tr>
<td>Mo</td>
<td>42</td>
<td>95.94</td>
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<tr>
<td>W</td>
<td>74</td>
<td>183.84</td>
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Ferrium M54
Superior Properties

• Benefits of using M54 vs. 4340 and Maraging steels:
  – Greater strength-toughness combination
  – Greater resistance to Stress Corrosion Cracking (SCC)
  – Superior low and high cycle fatigue life

• AMS 6516; MMPDS S Basis

• Significant DoD support for M54
M54: Improved Typical Properties vs. Incumbent Oil & Gas Alloys

<table>
<thead>
<tr>
<th></th>
<th>300M</th>
<th>4340</th>
<th>Maraging 250</th>
<th>Ferrium M54</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ultimate Tensile</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Strength (ksi)</td>
<td>288</td>
<td>276</td>
<td>265</td>
<td>293</td>
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<tr>
<td><strong>0.2% Yield Strength</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(ksi)</td>
<td>245</td>
<td>222</td>
<td>250</td>
<td>251</td>
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<tr>
<td><strong>$K_{IC}$</strong> Fracture**</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Toughness (ksi-$\sqrt{\text{in}}$)</strong></td>
<td>65</td>
<td>50</td>
<td>92</td>
<td>118</td>
</tr>
<tr>
<td><strong>$K_{ISCC}$</strong> (ksi-$\sqrt{\text{in}}$)</td>
<td>15</td>
<td>10</td>
<td>45</td>
<td>85</td>
</tr>
</tbody>
</table>

M54 has greater strength, toughness and SCC resistance versus 4340/300M and Maraging 250
M54: Much Greater Low & High Cycle Stress-Controlled Fatigue Life vs. 300M / 4340

Stress-controlled fatigue testing ($K_I = 1$, $R = -0.33$, longitudinal, $f = 10$ or $20$ Hz)

**Ferrum M54 vs. 300M**

(300M data from Aerospace Structural Metals Handbook)

- **M54, heat treated, ground, non-shot peened (Questek data)**
- **300M, heat treated, ground, shot peened**
- **300M, heat treated, ground, non-shot peened**

Large increase in threshold stress
M54: Similar Fatigue Life Vs. Maraging 250, But With Greater Toughness and SCC Resistance
M54: T-45 and F-18 Jet Applications

- Navy SBIR N07-032 currently evaluating M54 for production of T-45 hook shanks
  - Component manufacturing near completion and to be rig tested by Navy in summer 2013
  - Initial production run expected in 2014
- Navy SBIR N093-175 currently evaluating M54 for production of F-18 hook points
  - Prototype hook point fabrication completed
  - Rig testing expected in late 2013

Photo courtesy of theaviationist.com
## M54 Design and Development Timeline

<table>
<thead>
<tr>
<th>Milestone</th>
<th>Date</th>
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<tbody>
<tr>
<td>Created System Design Chart (Design Goals)</td>
<td>Aug. 2007</td>
</tr>
<tr>
<td>300 lb prototype proof-of-concept production</td>
<td>Jun. 2008</td>
</tr>
<tr>
<td>Feasibility to meet static property requirements</td>
<td>Sep. 2008</td>
</tr>
<tr>
<td>Multi-ton full-scale ingot production</td>
<td>Jul. 2009</td>
</tr>
<tr>
<td>Static property data development</td>
<td>Jan. 2011</td>
</tr>
<tr>
<td>Metallic Materials Development and Standardization (MMPDS)</td>
<td>~ 2013</td>
</tr>
</tbody>
</table>

Less than 2 years from definition of design goals to full-scale ingot production
**Ferrium S53® - Summary**

- Ultra High-Strength, Corrosion Resistant Steel
- Replace 4340/300M/Maraging Series where similar strength is needed but components are corroding; eliminate Cad usage
- Replace 440C where greater toughness / ductility is required
- Corrosion rate of 0.33 mpy, vs. 0.26 for 15-5 PH and 7.0 for 300M
- In landing gear flight service today without cadmium plating

<table>
<thead>
<tr>
<th>Typical Alloy Properties</th>
<th>YS (ksi)</th>
<th>UTS (ksi)</th>
<th>El (%)</th>
<th>RA %</th>
<th>Fracture Toughness (ksi-√in)</th>
<th>Corrosion Resistance</th>
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</thead>
<tbody>
<tr>
<td><strong>300M</strong></td>
<td>245</td>
<td>288</td>
<td>9</td>
<td>31</td>
<td>65</td>
<td>Poor</td>
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<tr>
<td><strong>4340</strong></td>
<td>222</td>
<td>276</td>
<td>11</td>
<td>35</td>
<td>50</td>
<td>Poor</td>
</tr>
<tr>
<td>Maraging 250</td>
<td>250</td>
<td>265</td>
<td>12</td>
<td>55</td>
<td>92</td>
<td>Poor</td>
</tr>
<tr>
<td><strong>440C</strong></td>
<td>275</td>
<td>285</td>
<td>2</td>
<td>10</td>
<td>15</td>
<td>Good</td>
</tr>
<tr>
<td><strong>Ferrium S53®</strong></td>
<td>225</td>
<td>288</td>
<td>15</td>
<td>57</td>
<td>65</td>
<td>Good</td>
</tr>
</tbody>
</table>
Successful 18-Month Duration S53 Landing Gear Field Service Evaluation Completed

- No cadmium, only prime-and-paint, aircraft based at NASA's Johnson Space Center (Gulf Coast).
- S53 (Cad free; prime and paint only) performed as well or better vs. 4340 (Cad-plated, prime and painted).
- Continue to evaluate performance, ongoing service evaluation.

Subjected to 307 sorties, 541 landings, 44 total tire changes – No defects or rust found.

- Also flying on A-10. KC-135 & C-5 landing gear awaiting evaluation.
**Ferrium® C61 & C64 High Performance Carburizing Steels**

Upgrade from 9310 and 8620

**C61 (AMS 6517):** 60-62 HRC case, high-strength & high-toughness core

**C64 (AMS 6509):** 62-64 HRC case, high-strength core

- High tempering temperature → greater temperature resistance
- Greater corrosion resistance than incumbent alloys
- For gears, shafts, integrally-geared shafts, pins, ball screws, etc.
- Designed for vacuum carburization

<table>
<thead>
<tr>
<th>Typical Alloy Properties</th>
<th>YS (ksi)</th>
<th>UTS (ksi)</th>
<th>Core Hardness (HRC)</th>
<th>El (%)</th>
<th>RA %</th>
<th>Fracture Toughness (ksi√in)</th>
<th>Achievable Surface Hardness (HRC)</th>
<th>Tempering Temperature (°F)</th>
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<tbody>
<tr>
<td>AISI 9310</td>
<td>155</td>
<td>175</td>
<td>34-42</td>
<td>16</td>
<td>53</td>
<td>85</td>
<td>58-62</td>
<td>300</td>
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<td>AISI 8620</td>
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<td>41-48</td>
<td>14</td>
<td>53</td>
<td>-</td>
<td>61</td>
<td>450</td>
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<td>225</td>
<td>240</td>
<td>48-50</td>
<td>16</td>
<td>70</td>
<td>130</td>
<td>60-62</td>
<td>900</td>
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<tr>
<td><strong>Ferrium® C64</strong></td>
<td>199</td>
<td>229</td>
<td>48-50</td>
<td>18</td>
<td>75</td>
<td>85</td>
<td>62-64</td>
<td>925</td>
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</table>

**Commercially Available**

[CARPENTER Logo]

[Questek Innovations LLC Logo]
C61 and C64 Applications To Date or In Evaluation

Notable C61 Applications

- CH-47 Chinook helicopter forward rotor shaft application under SBIR Phase II
- Evaluated in U.S. Army-funded Enhanced Rotor Drive Systems (ERDS) program
  
  “Based on all the test data and on Boeing’s analysis, C61 has been selected by Boeing as the gear steel for the final ERDS demonstrator test gearboxes”

- Off-road racing Ring & Pinion class 1/2-1600: 100+ installations, observed 3-4x life increase vs. 9310

Notable C64 Applications

- Evaluation with Bell Helicopter in U.S. Army-funded Future Advanced Rotorcraft Drive System (FARDS) program
- Racing gear components where 9310 fails by surface pitting
High Hardenability of C61 and C64

• High hardenability of *Ferrium* allows for direct gas quenching and
  - Eliminate oil quench and hardening steps
  - Slower cooling rate → reduced distortion
• Reduced distortion → less grind stock removal → lower costs
Superior Axial Fatigue Performance vs. 9310

From U.S. Army Contract #W911W6-09-C-0001
C61: Better High-Temperature Strength vs. Pyrowear 53

![Graph showing stress vs. temperature for different materials](image-url)
Energy and Oil & Gas Related Applications and Materials Development Projects
Applications

- Oil Field Components
  - Load shafts
  - Drill tools
- Case running tools and shafts
- Downhole components
  - Drilling gears
  - Transmission gears, rings and pinions

72’ long oil and gas case running shaft produced from M54
U.S. Department of Energy - Energy and Oil & Gas Related Projects

• Weldable, High-Cr Ferritic Steel for Coal-Fired Power Plants Application
• U.S. Department of Energy-funded SBIR Phase II program underway
• Original design goals:
  – Design and develop materials that can operate at increased steam temperature and pressure in supercritical boilers to increase fuel efficiency and reduce carbon emission
• Phase I results demonstrated:
  – improved high-temperature tensile strength over incumbent P92
  – thermally stable as-welded microstructure without PWHT
• Phase II:
  – Initial prototype scale alloys currently in production
High Performance, Low Cost, Low Loss Soft Magnetic Alloy for Traction Drive Motor Applications

U.S. Department of Energy-funded SBIR Phase I program underway

Original design goals:
- Design and develop a soft magnetic alloy with high-strength capability of operating at high speeds, achieving significant cost savings to approach DOE motor cost target of $4.7/kW in 2020

Phase I:
- Final alloy designs achieved
- Button scale coupon testing complete
U.S. Department of Energy - Energy and Oil & Gas Related Projects

- Castable SX Ni-based Superalloys for IGT Blade Components
- U.S. Department of Energy-funded SBIR Phase I program underway

Original design goals:
- Explore compositional adjustments to Nickel based superalloys used in single crystal gas turbine components that will increase the yield rates of single crystal castings for high-temperature applications

Phase I:
- Final alloy designs achieved
- Prototype alloy casting underway
- Final inspection and analysis in November marks end of project
Computational Design of New High Performance Steels for Next-Generation Natural Gas Pipelines

• The increase in demand for natural gas demands the development of new pipeline materials with enhanced properties.
• QuesTek is applying its computational alloy design methodology to design an optimized high-strength, low-alloy (HSLA), high-toughness, low-hardness pipeline steel that demonstrates superior corrosion resistance, weldability, and high-temperature performance to meet 2025 performance goals in the natural gas pipeline industry, including:
  (1) the ability to handle increased pressure (50 – 75 ksi),
  (2) improved corrosion resistance (specifically H2S and CO2 environments),
  (3) improved weldability,
  (4) improved high temperature performance ( >550°F),
  (5) improved toughness and strength at low temperatures (e.g. North Sea or Arctic conditions);
  (6) optimized heat treatment process, and
  (7) enhanced mechanical performance (sour service yield strength of 120 K).
Materials Under Development
**Ferrium PH48S™ Castable Stainless Steel**

- Martensitic, maraging, precipitation-hardening, casting stainless steel designed and developed under USMC SBIR
- Exceeds strength to weight ratio of Ti6-4 but at lower cost
- Equivalent strength of conventional high strength steels, with greater corrosion resistance
- High Charpy impact toughness at low temperatures and good ductility ensured through low DBTT of -80°C

<table>
<thead>
<tr>
<th>Material</th>
<th>Processing</th>
<th>Yield Strength (ksi)</th>
<th>Ultimate Tensile (ksi)</th>
<th>$K_I$ (ksi√inch)</th>
<th>$K_{ISCC}$ (ksi√inch)</th>
<th>Density (lb/in$^3$)</th>
<th>Specific YS (in * $10^5$)</th>
<th>Specific UTS (in * $10^5$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PH48S</td>
<td>Cast</td>
<td>220</td>
<td>230</td>
<td>90</td>
<td>&gt;75</td>
<td>0.288</td>
<td>764</td>
<td>799</td>
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<tr>
<td>Ti6-4</td>
<td>Cast (1550F)</td>
<td>112</td>
<td>124</td>
<td>95</td>
<td>&gt;58</td>
<td>0.161</td>
<td>696</td>
<td>770</td>
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<tr>
<td>13-8</td>
<td>Wrought (H1000)</td>
<td>205</td>
<td>215</td>
<td>98</td>
<td>&gt;90</td>
<td>0.279</td>
<td>735</td>
<td>771</td>
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<tr>
<td>13-8</td>
<td>Cast</td>
<td>195</td>
<td></td>
<td></td>
<td></td>
<td>0.279</td>
<td>699</td>
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Ferrium N63 Surface-Hardenable Stainless Steel

- U.S. Navy-funded SBIR Phase I Base program completed
- Demonstrated ideal combination of corrosion resistance, high surface hardness (61 HRC) and core strength and ductility; promising for bearing applications
- Improvement in corrosion resistance and toughness over 440C
- Alloy design refinements promise further improvement of corrosion resistance and potential for fully-stainless behavior

<table>
<thead>
<tr>
<th>Alloy</th>
<th>0.2% YS (ksi)</th>
<th>UTS (ksi)</th>
<th>%elong</th>
<th>%RA</th>
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<tbody>
<tr>
<td>N63-2A</td>
<td>171</td>
<td>222</td>
<td>23</td>
<td>71</td>
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<tr>
<td>N63-2B</td>
<td>162</td>
<td>207</td>
<td>24</td>
<td>74</td>
</tr>
<tr>
<td>Pyrowear 675</td>
<td>154</td>
<td>185</td>
<td>20</td>
<td>73</td>
</tr>
<tr>
<td>440C</td>
<td>275</td>
<td>285</td>
<td>2</td>
<td>10</td>
</tr>
</tbody>
</table>
QuesTek Be-free High Strength Alternative Alloys

Computationally-designed high-strength, low-friction, environmentally benign BeCu replacement alloys that eliminate health concerns:

**QuesTek-Co**: Co-Cr alloy

- Comparable yield strength; superior tensile strength, ductility and frictional behavior vs. commercially-available BeCu alloys

**Cuprium™**: Cu alloy

- Comparable yield and tensile strength, ductility and frictional behavior vs. commercially-available BeCu alloys

<table>
<thead>
<tr>
<th>Property</th>
<th>Cu-Be (Cu-1.9 Be)</th>
<th>QuesTek Cuprium™</th>
<th>QuesTek-Co (Co-Cr)</th>
<th>ToughMet® 3 (Cu-15Ni-8Sn)</th>
<th>BioDur® CCM (Co-Cr-Mo)</th>
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</thead>
<tbody>
<tr>
<td>0.2% Yield Strength</td>
<td>140 ksi (minimum) (non-CW)</td>
<td>~130 ksi demonstrated* (non-CW)</td>
<td>~130 ksi demonstrated (non-CW)</td>
<td>107 ksi (minimum) (non-CW)</td>
<td>85 ksi (non-CW) (typical)</td>
</tr>
<tr>
<td>Elongation</td>
<td>3 - 8%</td>
<td>~16% demonstrated*</td>
<td>TBD* (&gt;10%)</td>
<td>3 – 10%</td>
<td>26%</td>
</tr>
<tr>
<td>Wear Ranking</td>
<td>3 (worst)</td>
<td>2</td>
<td>1 (Best)</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>
Summary

- QuesTek is a global leader in integrated computational materials engineering (ICME) and has proven ability to design new ultra-high performance alloys to meet specific property targets.
- Incorporation of QuesTek’s aerospace alloys for demanding Oil & Gas applications may provide better performance, improve safety and reduce risk.
Thank You

Questions?

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847-425-8241, jgrabowski@questek.com
(Technical support)