Flexible Operation and Future Options for Fossil Power Generation

Impacts on Valves due to Changing Mission Profile

John Shingledecker, Ph.D
Senior Program Manager, Cross-Sector Technologies
Electric Power Research Institute

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Introduction to EPRI

Go to www.epri.com for more information
EPRI’s Mission

Advancing safe, reliable, affordable, and environmentally responsible electricity for society through global collaboration, thought leadership and science & technology innovation.
Three Key Aspects of EPRI

**Independent**
Objective, scientifically based results address reliability, efficiency, affordability, health, safety, and the environment

**Nonprofit**
Chartered to serve the public benefit

**Collaborative**
Bring together scientists, engineers, academic researchers, and industry experts
EPRI Membership & Funding

- 450+ participants in more than 30 countries
- EPRI members generate approximately 90% of the electricity in the United States

December 31, 2015

Investor-Owned: 59%
International: 25%
Federal/State: 6%
Municipal: 5%
Cooperative: 4%
Independent Power Producer: 1%
EPRI’s Role

Stimulate innovation; help accelerate technology development
Conducting Research Today

Environment

- Environmental Sciences: Air and Multimedia
- Environmental Sciences: Groundwater and Land Management
- Environmental Sciences: Water and Ecosystems
- Strategic Analysis and Technology Assessments
- Workforce and the Public: Health Assessment and Safety
- Renewables
- Sustainability

Generation

- Advanced Fossil Plants, Carbon Capture, Utilization, and Storage
- Combined Cycle
- Environmental Controls
- Major Component Reliability
- Materials and Chemistry
- Operations and Maintenance
- Power Plant Water Management
- Renewable Energy

Nuclear

- Advanced Nuclear Technology
- Chemistry and Radiation Safety
- Equipment Reliability
- Fuel Reliability
- Long-Term Operations
- Materials Degradation/Aging
- Nondestructive Evaluation and Material Characterization
- Risk and Safety Management
- Used Fuel and High-Level Waste Management

Power Delivery and Utilization

Distribution and Energy Utilization

- Distribution
- Energy Utilization
- Information, Communication, and Cyber Security

Transmission

- Grid Operations and Planning
- Transmission and Substations
Integrated Energy Network: Three Evolving Infrastructures

Using Cleaner Energy and Electrification

Producing Cleaner Energy

Integrating Energy Resources

Integrated Energy Network
A Network of Infrastructures that connects customers with clean energy production and use
EPRI Scenario Planning

Scenario Planning (2006–2007)
- PRISM – Clean Electricity Generation Portfolio
- Demo Projects

Scenario Planning (2012–2013)
- Power System Transformation
- Integrated Grid

Scenario Planning Refresh (Now)
- Stress Test PRISM
- Integrate Grid

Align the R&D Portfolio and Business Model with Vision of the Future
Scenarios Define the Envelope of Plausible Futures

Economic Recession: A future with sustained low or negative trending economic growth (GDP) and/or global conflict.

Consumer Drive: A future where consumer desire for continuous improvement in quality of life dominates the focus of new products.

Fossil Fuel Abundance: A future where fossil fuels remain low cost and supply is abundant, recognizing that supply differs among global regions.

Deep Decarbonization: A future where international agreement that significant changes are needed to address climate change leads to a push for even cleaner energy.

Each scenario is defined by five markers:
1. Fossil Fuel Price
2. Energy and Environmental Policy
3. Demand for Grid Supplied Electricity
4. Technology Innovation
5. International Impact
Global Points of View

Energy and Emission
- Reducing emission will remain a long-term global issue
- Overall global energy demand will grow – flat/declining in OECD; growth in non-OECD

Efficiency and Renewables
- Energy use and GDP will continue to decouple as efficiency gains across all energy use
- Renewable technology cost will decrease and global penetration level will continue to increase

Customer Expectations
- Choice, control, comfort, and convenience will be primary drivers
- The internet of things will digitally connect every customer with every thing
- Increased dependence on electricity will demand higher reliability and quality and higher energy infrastructure resiliency against physical/cyber/natural disaster

Water
- Increasingly water-constrained future over the long term
- Water energy interfaces will continue to expand

Black and White Swans…
Expect the Unexpected
Low-carbon Generation Plus Electrification by 2050

**Generation (TWh)**

- **Coal**
- **Gas**
- **Gas-CCS**
- **Nuclear**
- **Hydro+**
- **Wind**
- **Solar**

Significant changes after 2030

**Capacity (GW)**

- **Peak Load**
- **Residual Peak**

Just One Potential Scenario
Illustrative U.S. Scenario of 70% Emission Reduction by 2050

Final Energy

CO₂ Emissions
(from final energy and electric generation)*

- **Reference**: Elec 4757 TWh, Gas 3004 TWh, Oil 53 TWh, Other 22 TWh
- **Low-Carbon**: Elec 6804 TWh, Gas 2062 TWh, Oil 122 TWh, Other 22 TWh

- **43% Increase in Electric Generation Compared to Reference Case**

- **70% Decrease in Economy-wide CO₂ Emissions Compared to Reference Case**


Efficiency and Electrification Key to Emission Reduction
Pathway to 2050 – The Need for New Technologies

Generation IV Nuclear
(co-production – electricity, hydrogen steam)

High-Altitude Wind

Large-Scale Storage
(e.g., Regenesys Flow Battery)

Coal and Gas Carbon Capture and Sequestration

Gen III Photovoltaic (PV)
(e.g., High power density PV cells)

Source: Carbon Capture Image – htc02systems.com; Gen IV Image – KAERI
Electrification is the Pathway to Economy-wide CO$_2$ Reductions
Changes in Fossil Power Generation

Near and Transformative Challenges
Flexibility – A New Reality for Powerplants
(Example from CAISO impact of Increasing Solar PV)

CAISO – 2012 Actual Net Load Demand

- Baseload Demand: 18,000 MW
- Peak Ramping Rate: ~1000 MW per hour
- Peak Demand: 24,000 MW
- Daily Total Energy: 498,000 MWh

CAISO – 2020 Modeled Net Load Demand

- Baseload Demand: 12,000 MW
- Peak Ramping Rate: >5000 MW per hour
- Peak Demand: 26,000 MW
- Daily Total Energy: 459,000 MWh

Net Load: Actual Power Demand on the Grid, less the power provided by non-dispatchable generation (e.g. solar and wind)
Some Effects of Flexibility and the Changing Mission of the Fossil Fleet (Existing and New Units)

- **Reduction in overall Output** = Less money/MW = improved needs for maintenance optimization/cost reduction & sensor technologies
- **More low-load operation** = reduction in efficiencies = component operation and damage challenges
- **More rapid start-ups** = more component damage
- **More cycling** = more wear and tear
Extreme Conditions are Required for Future Power Plants to Reduce CO₂ Emissions

Increased Efficiency is a Least Regret Strategy for CO₂ Reduction

Studies show A-USC = 10-35% reduction in CO₂ compared to current plants
New Power Cycles: Supercritical CO\textsubscript{2} (sCO\textsubscript{2}) Brayton Cycles

Similar conditions to A-USC Boilers/Turbines

**NET Power Cycle 25MW Demo**
- Gas-Fired 100\% Carbon
- Capture Modified CO\textsubscript{2} Brayton Cycle utilizing Inconel 740H for High-Temperature CO\textsubscript{2} piping

**CO\textsubscript{2} Critical Properties:**
- Temperature: 31°C (88°F)
- Pressure: 74 bar (1055 psig)
- Compressibility Factor: 29\% @ 38°C, 76 bar

**Advantages:** High Efficiency, Small Turbomachinery

**Challenges:** Materials, Heat Exchanges, Erosion

Partners: NET Power, CB&I, Toshiba, Exelon

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EPRI Materials R&D to Enable the Valves for the Changing Mission

Acknowledgements:

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Our many EPRI members who contributed materials, samples, and financial support for this R&D
What does this flexible operation mean for high-temperature materials in valve components?

- **New Damage Modes**
  - Industry challenges with hardface disbonding

- **More Erosion**
  - Higher-velocities during part-load operation
  - More oxide spallation

- **More Oxidation**
  - Higher-temperatures

- **More Wear**
  - Less static and more dynamic operation

- **Alternative Material Solutions are Needed for Todays and Tomorrows Plants**
Recent Experience in Combined Cycle Plants

- Numerous Reports on valve hardfacing disbonding
  - Significant cracking reported
  - No trend with operating hours
  - Not one design or manufacturer

- 20 sites document in EPRI survey
  - Many more undocumented by word of mouth and multiple failures at same site

- Disbonding hardfacing can lead to damage downstream
  - Replacement / refurbishment of valves
  - Lost generation
  - Damage to other components

- HP Steam-Turbine Blade Damage from ‘Liberated’ Hardfacing

Type 1 – Disbonding between substrate and hardfacing
Type 2 – Transverse (through-hardfacing) cracking
Why now?

Traditionally:
- Large Coal-Fired Boilers
  - Few transients (base load)
  - Moderate temperatures (<1000F, <538C)
  - Grades 11 and 22 (CrMo)
  - Simple piping systems

- Processing
  - Traditionally SMAW and GTAW

What has changed?

Recently:
- More combined cycle plants
  - Faster startes
  - Higher temperatures (>1000F, >538C)
  - Higher alloys (Grade 91: 9Cr1Mo)
  - Complex piping and operation: (ex: 2on1 operation)

- Processing
  - Increased use of auto-PTAW

Application space for Co-based hardfacing is expanding:

Higher temperature operation a significant contributor.
Project Summary

- Conclusion of 3 year EPRI study
  - Utility and OEM member engagement
  - Over 20 donated parts
  - 9 thorough ex-service evaluations + 12 historical reports

- Technical work completed

- Several reports available
  - Manufacturing guideline (3002004990) published and in use
  - Field experience overview (3002004991) released March 2015
  - Detailed analyses for avoiding this issue (3002004992) Dec. 2015

- Currently in field validation phase
Background on Test Methods for High-Temperature Erosion

- ASTM G211 (2014)
- First High-Temp. Erosion Test Standard
  - Result of EPRI Sponsored Round Robin Test Program
  - 7 Labs, 2012 EPRI Workshop

3D Laser Profilometry: full area scan

- Analyze for texture, surface roughness
- Max depth and volume loss calculations
- 5 nm special resolution
- Process takes only minutes but gives high resolution data in air

Application to Erosion, sliding wear, and galling
Plasma-Enhanced Magnetron Sputtering (PEMS) Nanocoatings

- Nano-scale grain structure from PEMS
  - Dense, thin; very hard and tough
  - Improved erosion / wear / oxidation properties compared to conventional coatings (room temp)

- EPRI studying TiSiCN coatings up to 20 µm (0.0008 inches) in thickness
High-Temperature Solid Particle Erosion Testing

- ASTM G211; 210 m/s (650 ft/s), 625°C (1150°F)
- 30° incident, Fine Chromite ~50µm

<table>
<thead>
<tr>
<th>Material</th>
<th>Baseline 410SS</th>
<th>Alloy 901</th>
<th>Alloy 718</th>
<th>Waspalloy</th>
<th>TiSiCN</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Base</td>
<td>2.31</td>
<td>3.23</td>
<td>3.23</td>
<td>3.00</td>
<td>0.033</td>
</tr>
<tr>
<td>Nitrided</td>
<td>3.30</td>
<td>3.14</td>
<td>3.06</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Industry Standard Nitriding for Surface Hardening has Little Effect on High-Temp. Erosion; Nano-coating was not Breached
TiSiCN Nanocoatings Field Trial

- Original part (nitrided) operated for 15,000 hours over 12 starts
  - Experienced 30% loss of cross section (0.15”)
- Replaced with 20 µm TiSiCN Nanocated stem of same geometry
- Operated for 17,000 hours and 11 starts
  - Sample shows damage but more resilient than without coating
  - Appears that erosion localizes once the coating is broken

**Additional optimization and field trials ongoing due to promising results**

<table>
<thead>
<tr>
<th></th>
<th>Area Measured (mm²)</th>
<th>Eroded Volume (mm³)</th>
<th>Eroded Volume per 100mm² (mm³)</th>
<th>Average Depth of Erosion (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Old Stem (no coating)</td>
<td>49</td>
<td>303</td>
<td>618</td>
<td>6.2</td>
</tr>
<tr>
<td>Stem with 30 micro thick nanocoating</td>
<td>75</td>
<td>194</td>
<td>259</td>
<td>2.6</td>
</tr>
<tr>
<td>Improvement in Erosion Resistance due to coating</td>
<td></td>
<td>1.6</td>
<td>2.4</td>
<td>2.4</td>
</tr>
</tbody>
</table>
Oxidation & Wear R&D
State of the Industry - Materials

- Alloy selection stagnant in the industry
  - Decades of experience in *non-flexible* operation
  - Selection based primarily on temperature
- Nitriding surface treatment popular
  - Provides excellent sliding wear, anti-galling, and low friction
  - What about oxidation?

<table>
<thead>
<tr>
<th>General Electric</th>
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<tbody>
<tr>
<td>Nitr alloy 135M – (135M Nitrided)</td>
</tr>
<tr>
<td>AISI Type 410 Stainless Steel – Nitrided</td>
</tr>
<tr>
<td>AISI Type 422 Stainless Steel – Nitrided</td>
</tr>
<tr>
<td>EME – Nitrided</td>
</tr>
<tr>
<td>ASTM A 453 Gr 651 (19-9 DL) – Nitrided</td>
</tr>
<tr>
<td>Incoloy 901 – Nitrided</td>
</tr>
<tr>
<td>Siemens-Westinghouse</td>
</tr>
<tr>
<td>Nitr alloy 135M – (135M Nitrided)</td>
</tr>
<tr>
<td>AISI Type 422 Stainless Steel – Nitrided</td>
</tr>
<tr>
<td>AMS 5700 – Nitrided</td>
</tr>
<tr>
<td>Incoloy 901 – Nitrided</td>
</tr>
<tr>
<td>Refractalloy 26 – Nitrided</td>
</tr>
<tr>
<td>W-545 – Nitrided</td>
</tr>
</tbody>
</table>

EPRI Report #1016786

422: Nitride Thickness 260μm (10mil)
901: Nitride Thickness 60μm (2.4mil)
Increasing Flexible Operation has Resulted in Valve Operation and Reliability Challenges

- High temperature oxidation, a.k.a. Blue Blush
- Build up of oxide scale during operation
  - Affects clearances – tight to begin with
  - Can lead to valve sticking
  - Requires inspection and maintenance
- Want best possible operational dependability
Oxidation of Candidate Materials:

Steam Oxide Thickness and Morphology (625-650°C)

<table>
<thead>
<tr>
<th>Material</th>
<th>500h</th>
<th>1000h</th>
<th>2500h</th>
<th>3000h</th>
<th>4000h</th>
</tr>
</thead>
<tbody>
<tr>
<td>901</td>
<td>50μm</td>
<td></td>
<td>Irregular nodule formation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>901N</td>
<td>50μm</td>
<td></td>
<td>GB Penetration, 60 μm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>901T</td>
<td>50μm</td>
<td></td>
<td>Slow Growth on top of TiSiCN</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WASP</td>
<td>10μm</td>
<td></td>
<td>Uniform scale growth</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WASPN</td>
<td>50μm</td>
<td></td>
<td>Uniform scale growth</td>
<td></td>
<td></td>
</tr>
<tr>
<td>718</td>
<td>10μm</td>
<td></td>
<td>Uniform scale growth</td>
<td></td>
<td></td>
</tr>
<tr>
<td>718N</td>
<td>50μm</td>
<td></td>
<td>Uniform scale growth</td>
<td></td>
<td></td>
</tr>
<tr>
<td>740</td>
<td>10μm</td>
<td></td>
<td>Uniform scale growth</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Nitriding results in thicker oxide scales

Alternative nickel-based alloys show improved performance to 901
Higher-Temperature Operation: Wear Concerns Evaluated Materials

- Coatings manufacturers surveyed for “best candidate”
  - High temperature performance wear resistance 600 - 800 °C
  - Exceed capability of Stellite 6 (at 600 °C) - Baseline
- Applied to IN625 plate as substrate
- Testing performed on CSM High Temperature Tribometer
  - Capable up to 1000 °C
  - Volume loss measurements via 3D Laser Microscopy

<table>
<thead>
<tr>
<th>Material</th>
<th>Coating Process</th>
<th>Thickness µm (in)</th>
<th>Nominal Chemistry wt%</th>
<th>Hardness HV 500g</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stellite 6, PM-HIP</td>
<td>N/A</td>
<td>N/A</td>
<td>30 Cr, 5 W, 1.1 C, Bal Co</td>
<td>480</td>
</tr>
<tr>
<td>Diamalloy 4060NS</td>
<td>HVOF</td>
<td>770 (0.030)</td>
<td>28.5 Cr, 4.5 W, 1.1 C, 1.6 Si, Bal Co</td>
<td>570</td>
</tr>
<tr>
<td>WOKA 7103</td>
<td>HVOF</td>
<td>450 (0.018)</td>
<td>80% Cr₂C₃ + 20% (80 Ni, 20 Cr) matrix</td>
<td>970</td>
</tr>
<tr>
<td>Stellite 728</td>
<td>PTAW</td>
<td>5,000 (0.2)</td>
<td>24 Cr, 12 Mo, 6 Ni, 1.5 Nb, Bal Co</td>
<td>420</td>
</tr>
<tr>
<td>Triballoy T800</td>
<td>PTAW</td>
<td>5,000 (0.2)</td>
<td>18 Cr, 30 Mo, 3 Ni, 0.1 C, 3.5 Si, Bal Co</td>
<td>670</td>
</tr>
</tbody>
</table>
Example: Data Analysis on High Temperature Wear

- 3D Scans capture deepest point of the wear scar
- Stellite 6 shows poor wear resistance at higher temperatures
- Best performance goes to Diamalloy and WOKA

- Low CoF necessary for minimizing actuator size
- Stellite 6 is at about 0.3 at 600 °C
- Only WOKA and Stellite 728 show the same performance
EPRI Major Effort on Adoption of Powder-Metallurgy Hot Isostatic Pressing (PM-HIP) to Power Industry

- **PM HIP Advantages:**
  - Uniform structure = **Inspectibility**
  - **Near-net shaped** large components
  - Ability to **functionally apply materials**
  - Alternative manufacturing route

- **EPRI Led Efforts**
  - (2) FIRST EVER ASME B&PV Code Cases:
    - Allows PM-HIP for specific materials (now working on general application to all materials)
    - Engage supply chain
    - Major data development project
    - Confirmed inspectability
  - Demonstrations for advanced manufacturing (nuclear focus) – lowering costs, larger components, etc

- **Partners:**
  - Carpenter, BodyCote, Sandvik, Synertech, Erasteel, Tyco-Crosby, GE-Dresser, Areva, GEH, RR, Westinghouse, and others
Summary of EPRI Metallurgical Studies

- Flexible operation and the need for higher efficiency result in the need for more extreme valve material performance
- Testing by EPRI has shown
  - High-temperature erosion resistance can be improved by coatings with initial field trials in progress
  - There are alternative materials to today nitrided valve stem materials which show improved oxidation resistance which should lead to improved operational performance
  - Alternatives to Stellite 6 will need to be considered for wear behavior tomorrow’s power plants
  - Powder metallurgy processing is now code approved and opens new avenues for materials R&D
Final Summary

▪ The power generation industry and the entire *integrated energy network* will go through a major transformation over the next 30 years

▪ Currently flexible operation is changing the mode of operation and the mission of the fossil fleet

▪ Future plants will challenge materials and components with higher temperatures and more extreme conditions

▪ From the standpoint of valve components: the future clearly will require components capable for these extreme environments
Together…Shaping the Future of Electricity