High Quality, High Throughput Neutron Radiography Using Accelerator Based Neutron Generators

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Company Snapshot

• Phoenix delivers ion source and accelerator products and systems to several different markets

• Commercial systems have been fielded and are operating to specification:
  • Neutron radiography, neutron detector calibration, semiconductor ion implantation, medical isotope production

• Eight new systems are in process this year for commercial and government customers
  • Same applications as above plus radiation effects testing, fast neutron radiography IED detection, explosives detection, and nuclear fuel scanning
Neutron Radiography (N-ray)

- Non-destructive imaging technique complementary to X-ray
- Neutrons interact with atomic nucleus not electron cloud
  - Attenuation determined by elemental composition not material density
  - Certain materials have very high neutron attenuation
- What is the technical value of n-ray?
  - Provides unique material-to-material and material-to-background contrast resulting in unique information about a part
  - Particularly valuable when trying to view features inside high density (metal) containment
  - Allows detection of certain defects (cracks, voids, gaps, foreign material, assembly errors, etc) that cannot be detected with any other non-destructive method
X-Ray Radiograph (X-ray)

Neutron Radiograph (N-ray)

- X-rays and other existing nondestructive testing (NDT) methods have difficulty with certain known defects in these products:
  - Turbine blades
  - Cartridge actuated devices
  - Propellant actuated devices
  - Explosive transfer line
  - Frangible joints
  - Mild detonating fuse
  - Initiators
  - Electronic bridge wire detonators
  - Explosive bolts
  - Safe and arm switches
  - Warheads or projectiles with fragmenting shape charges
  - 0.50Cal/30MM Tracer and Incendiary Cartridges
  - Small and Medium Caliber Ammunition
  - 105-155mm artillery shells
  - Ceramic Body Armor
  - Internal liners or sealants
  - Liquid-Filled Cells (e.g., certain batteries)

- Many of these defect detection challenges could be solved with Phoenix neutron radiography systems

- Industry uses majority of existing n-ray capacity to examine turbine blades, energetic components and other high cost of failure parts
Available Neutron Sources

**Neutron Tubes & Isotopic**
- Isotope decay or low yield fusion produces neutrons
- Table top sized
- Limited Intensity
- Limited Applications

**Industrial Accelerators**
- High yield fusion or scattering reactions produce neutrons
- Room sized
- Moderate - high Intensity
- Simple regulations

**Nuclear Test Reactors and Large**
- Fission of uranium produces neutrons
- High Intensity
- Safety to public & personnel drives high regulatory burden & operating cost
- Produces spent nuclear fuel and other highly hazardous & costly wastes

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Neutrons/second:
- ~$100ks
- 10^6
- 10^7
- 10^8
- 10^9
- 10^10
- 10^11
- 10^12
- 10^13
- 10^14
- 10^15
- 10^16
- 10^17

Costs:
- ~$100MMs to $1B+
- ~$10MMs
- ~$100ks

Addressing the Challenge...Today

Phoenix has developed neutron radiography technology in collaboration with the Army over the last 10 years:

- First prototype delivered to Picatinny Arsenal in 2013
- Low Volume Prototype has been operating at Phoenix facility for past year
- Excellent image quality has been demonstrated on the prototype system
- Low Volume Pilot Unit shipping to Picatinny Arsenal in coming months
Phoenix Neutron Radiography Facility

- Phoenix is investing to build a one-of-a-kind facility...the Phoenix Neutron Imaging Center (PNIC)
- First operation fall 2019
- ATF Compliant & Permitted
- Compliant with DoD Ammunition & Explosives Safety and Security Manuals (4145.26 & 5100.76)
- Aerospace & defense quality programs for process and personnel (ISO9001, AS9100, NAS410, etc)
- On contract with Army & Navy to demonstrate high quality, high throughput thermal n-ray and fast n-ray this fall
Facility Detail

- System creates neutrons through a different reaction than previous systems
- Higher neutron yield system
  - Higher energy ... produces more intense ion beam
  - Plus advanced target, moderator & collimator designs
  - No tritium, uranium or other radioactive fuel
- Results in 100X higher thermal flux and higher neutron energy
  - 10 thermal beam ports reduce effective imaging time to minutes or seconds, depending on specimen size, materials and desired image quality
  - Fast neutron capability can penetrate components up to ~0.5m thick
  - End result is major throughput and versatility enhancements
- X-ray capability allows on-stop-shop for radiographic inspection
## Thermal N-Ray Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Nuclear Reactor (current baseline)</th>
<th>Phoenix DD System</th>
<th>Phoenix High Yield System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regulatory Burden</td>
<td>NRC Regulated</td>
<td>Minimal</td>
<td>Minimal</td>
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<tr>
<td>L/D Ratio</td>
<td>105</td>
<td>35</td>
<td>70 - 100</td>
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<tr>
<td>Thermal Neutron Flux @ Image Plane (n/cm²/s)</td>
<td>3.00E+06</td>
<td>1.12E+04</td>
<td>3.20E+05</td>
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<tr>
<td>Neutron : Gamma Ratio</td>
<td>&gt;1E6</td>
<td>MEDIUM</td>
<td>&gt;1E6</td>
</tr>
<tr>
<td>Cadmium Ratio</td>
<td>&gt;5</td>
<td>&lt;2</td>
<td>&gt;4</td>
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<tr>
<td>Time per Film Exposure (minutes)</td>
<td>5.6</td>
<td>1488.1</td>
<td>52.1</td>
</tr>
<tr>
<td>Time per CR Exposure (minutes)</td>
<td>3.8</td>
<td>1011.9</td>
<td>35.4</td>
</tr>
<tr>
<td>Annual Film Capacity (# Exposures)</td>
<td>&gt;20,000</td>
<td>&gt;3,000</td>
<td>&gt;25,000</td>
</tr>
<tr>
<td>Annual CR Capacity (# Exposures)</td>
<td>n/a</td>
<td>&gt;4,500</td>
<td>&gt;35,000</td>
</tr>
</tbody>
</table>

- **L/D =** length of collimator to diameter of aperture...Ensures high resolution
- **Flux =** number of neutrons / area...multiple imaging ports multiplies usable flux
- **N:gamma ratio =** want neutrons not gammas exposing film...important for ensuring high contrast
- **Cd ratio =** fast to thermal neutrons...important for ensuring high contrast
Fast Neutron Imaging

- Similar to high energy X-ray, ‘fast’ neutrons are high energy neutrons that can penetrate thicker & denser items

- Large caliber munitions, missiles and solid rocket motors
  - Need high penetration through thick metal cladding, warheads or fuel to view internal parts

- Bulk Cargo
  - Ports of entry, airport cargo, railway, military base protection
  - Can detect explosives, drugs and contraband with image and spectral analysis
Operation & Regulatory

- Simple operations...a single user interface, controlled by a single trained operator
- Common industrial hazards...flammable & compressed gasses, high voltages, ionizing radiation, pressure vessels
- No credible major accident scenarios...no nuclear meltdown, fission product release, etc.
- System has sensors and interlocks to protect machine and people...system shuts down in milliseconds
- Simple regulatory framework...no Nuclear Regulatory Commission license, state license/permit as with industrial X-ray units
- Common waste streams...no spent nuclear fuel or other wastes without disposal paths
Reactor Based Radiography Cycle

- Parts ready for inspection
  - Film & part quality reviewed. Accept or Reject.
  - Package for off-site shipment

- Parts arrive & unpacked
  - Transport to n-ray facility
  - Unpack parts & setup in fixtures

- Teardown fixture & repack
  - Transport to manufacturing facility
  - Manufacturer possession

- N-ray
  - Transporter possession

- N-ray Reactor possession

Key Considerations:

- 1-2 week typical duration + risks (weather, shipping deadlines, work loads)
- Multiple changes in custody and potential part traceability points-of-failure
- Multiple contracts, forms, travelers, etc
- Increasing costs in transport and n-ray service
- Export control, ITAR and IP concerns
- Little to no process flexibility
On-Site Accelerator Radiography Cycle

- Parts ready for inspection
- Hand-carry parts to n-ray station
- Setup in fixtures
- Film & part quality reviewed. Accept or Reject.
- N-ray
- Manufacturer possession

- Minutes - hours duration + no schedule risk
- No changes in custody or traceability issues
- No recurring contracts
- Cost reductions
- High process flexibility...in-process n-ray now a possibility
Conclusions

• Technology has leapt forward and current generation systems have achieved near reactor quality images

• Next generation system available in fall 2019 and expected to match or exceed reactor image quality while greatly improving throughput and maintaining low regulatory burden of previous systems

• PNIC facility offers a short-term remedy to a currently fragile supply chain for defense critical items

• To be efficient, inspections need to be deployed at the site of production, which Phoenix systems now allow
  ▪ 100% new product inspection or lot sampling
  ▪ Service life monitoring and extensions
  ▪ Failure analysis
  ▪ R&D and prototype support

• Phoenix technology allows the reinvigoration of valuable NDT technique that has gone dormant due to decades of decline in reactor access

• Bring us your inspection challenges…actively seeking industry partners for defect detection or sample imaging studies…energetics, munitions, fusing, additive manufacturing are full of potential n-ray applications
Phoenix
Transforming Nuclear Technology

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