PHOENIX
TRANSFORMING NUCLEAR TECHNOLOGY

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

NDIA Fuze Conference

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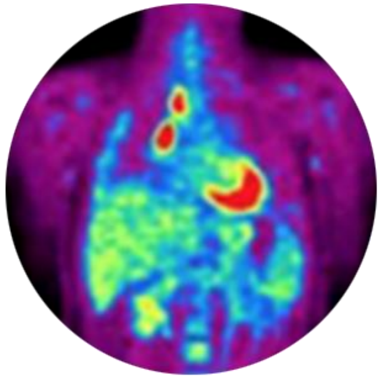
Brad Bloomquist
Director of Business Development
Phoenix, LLC

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



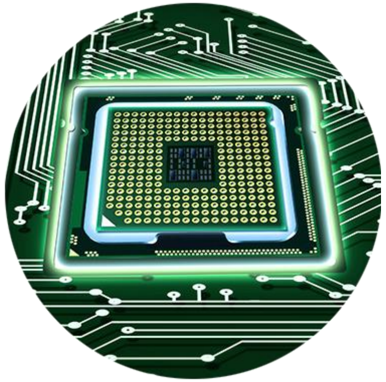
Medical

Non-Destructive Test

Defense

Aerospace

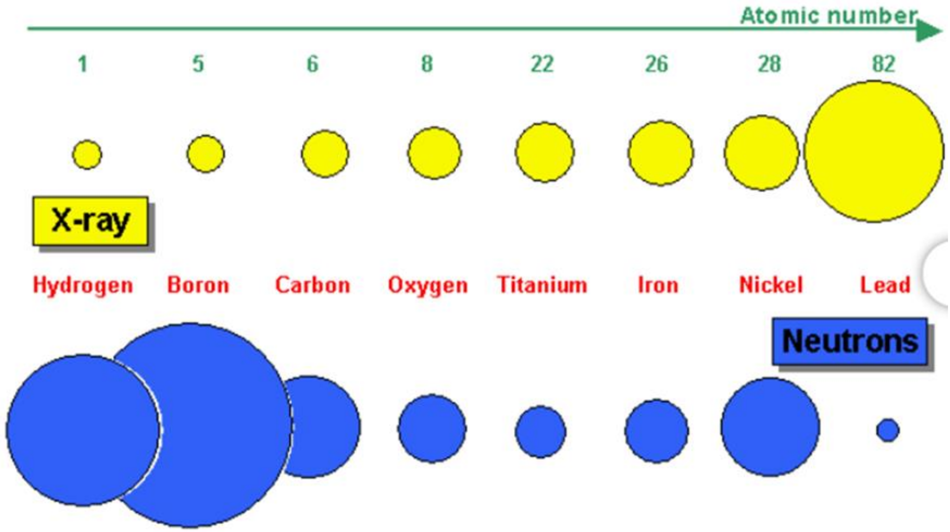
Nuclear QC & Calibration

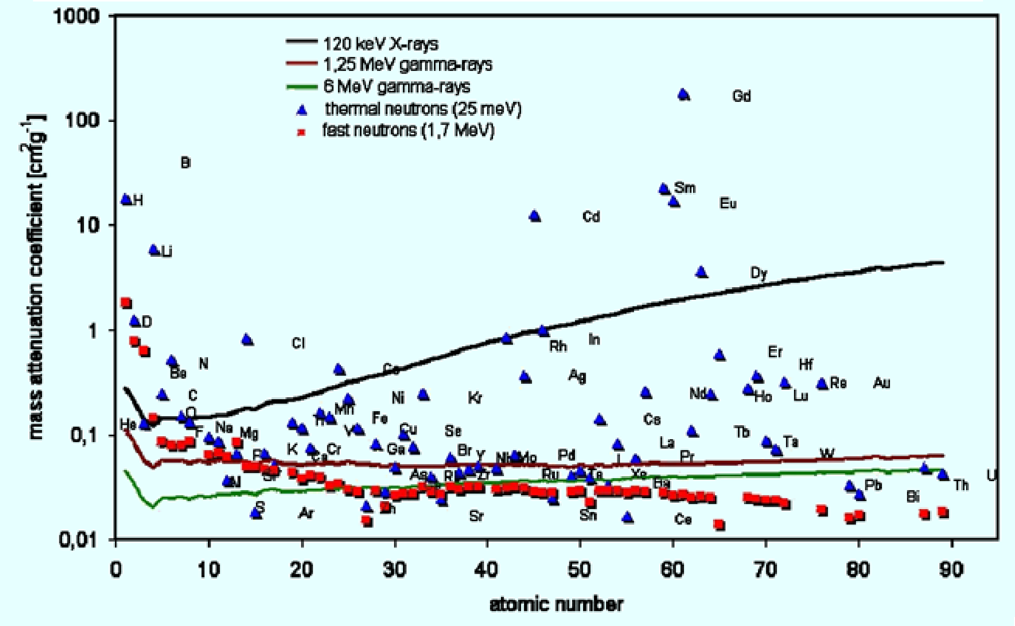


Semiconductor

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

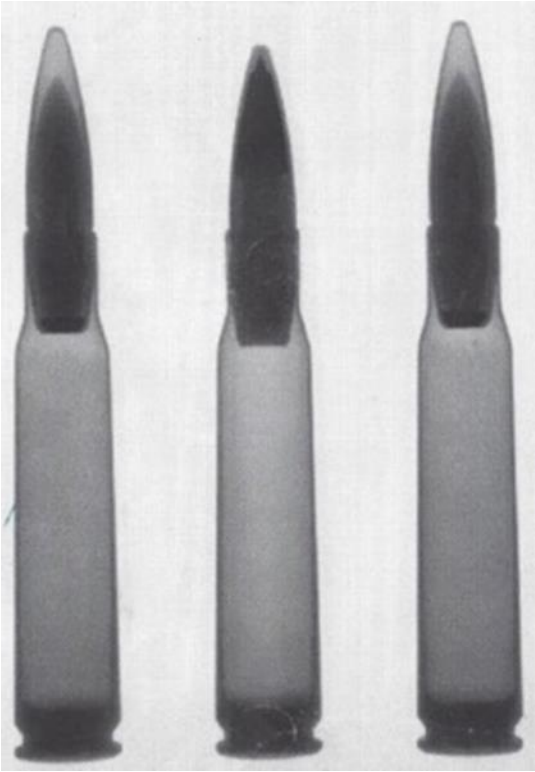




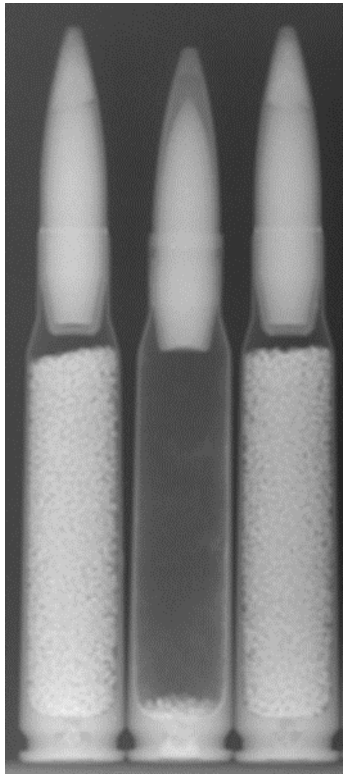
Why we do neutron radiography: The mass attenuation coefficient of elements

N-Ray Use Examples

X-Ray Radiograph (X-ray)



Neutron Radiograph (N-ray)



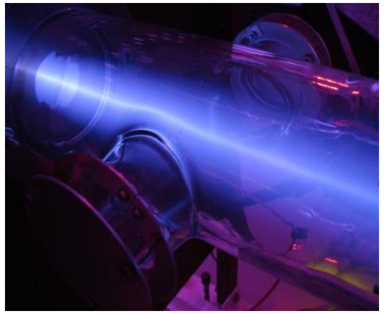
- X-rays and other existing nondestructive testing (NDT) methods have difficulty with certain known defects in these products:
  - Turbine blades
  - Cartridge actuated devices
  - Propellant actuated devices
  - Explosive transfer line
  - Frangible joints
  - Mild detonating fuse
  - Initiators
  - 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

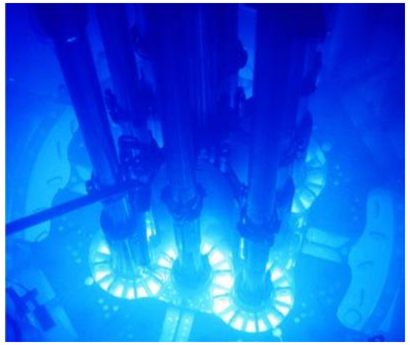
~$100ks

Industrial Accelerators



~MM-$10MMs

Nuclear Test Reactors and Large



~$100MMs to $1B+

10^{6} | 10^{7} | 10^{8} | 10^{9} | 10^{10} | 10^{11} | 10^{12} | 10^{13} | 10^{14} | 10^{15} | 10^{16} | 10^{17}

Neutrons/second

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

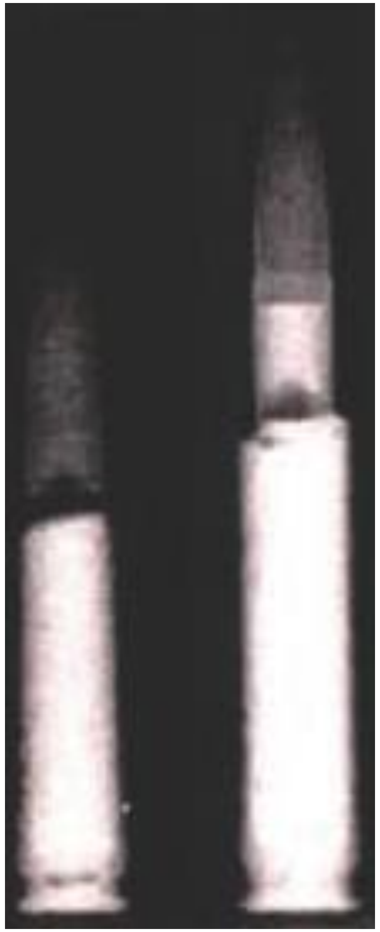
Addressing the Challenge…Today

- 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

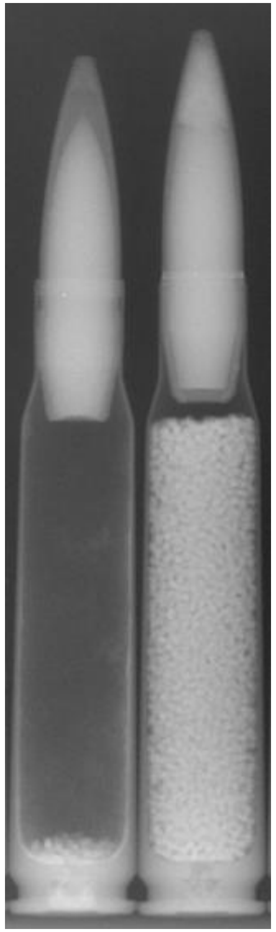
2013

2017

2013

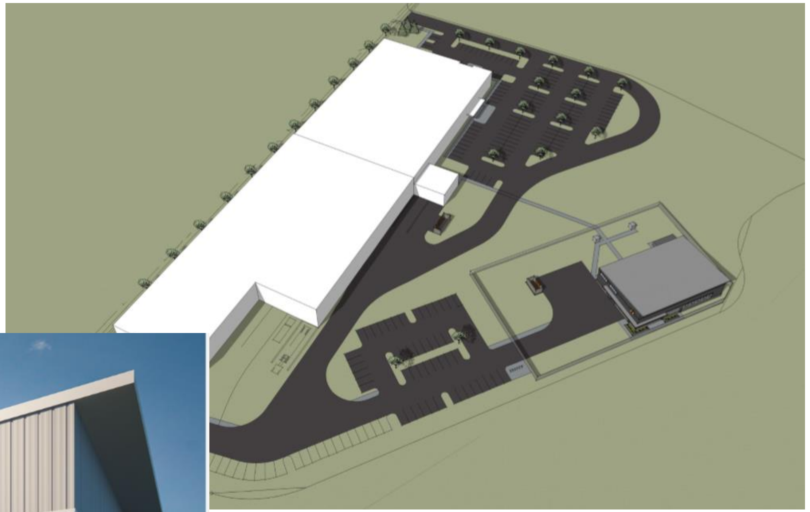


2017



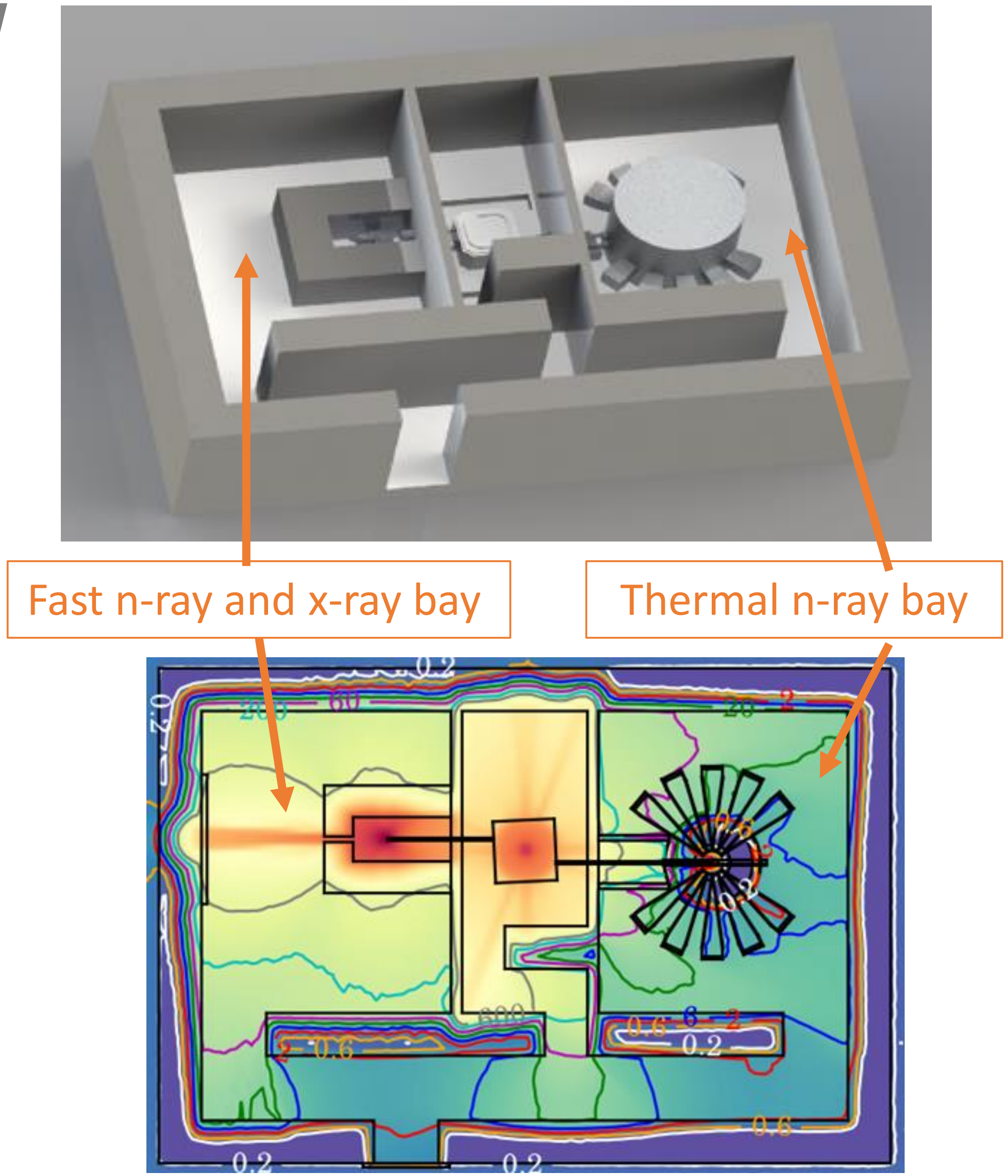
Phoenix Neutron Radiography Facility

- 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

L/D = length of collimator to diameter of aperture…Ensures high resolution

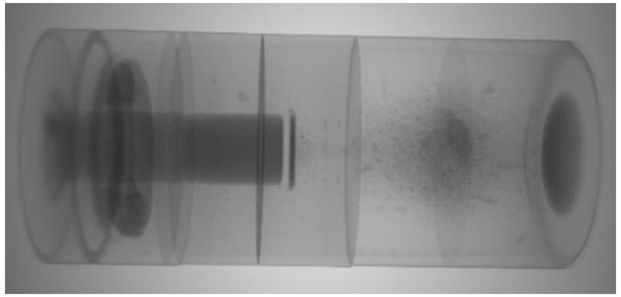
Flux = number of neutrons / area…multiple imaging ports multiplies usable flux

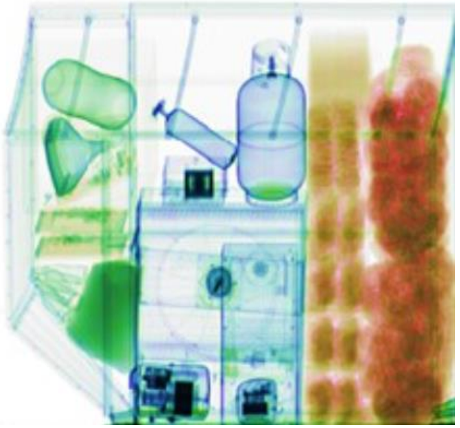
N:gamma ratio = want neutrons not gammas exposing film…important for ensuring high contrast

Cd ratio = fast to thermal neutrons…important for ensuring high contrast

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

Fast Neutron Imaging





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

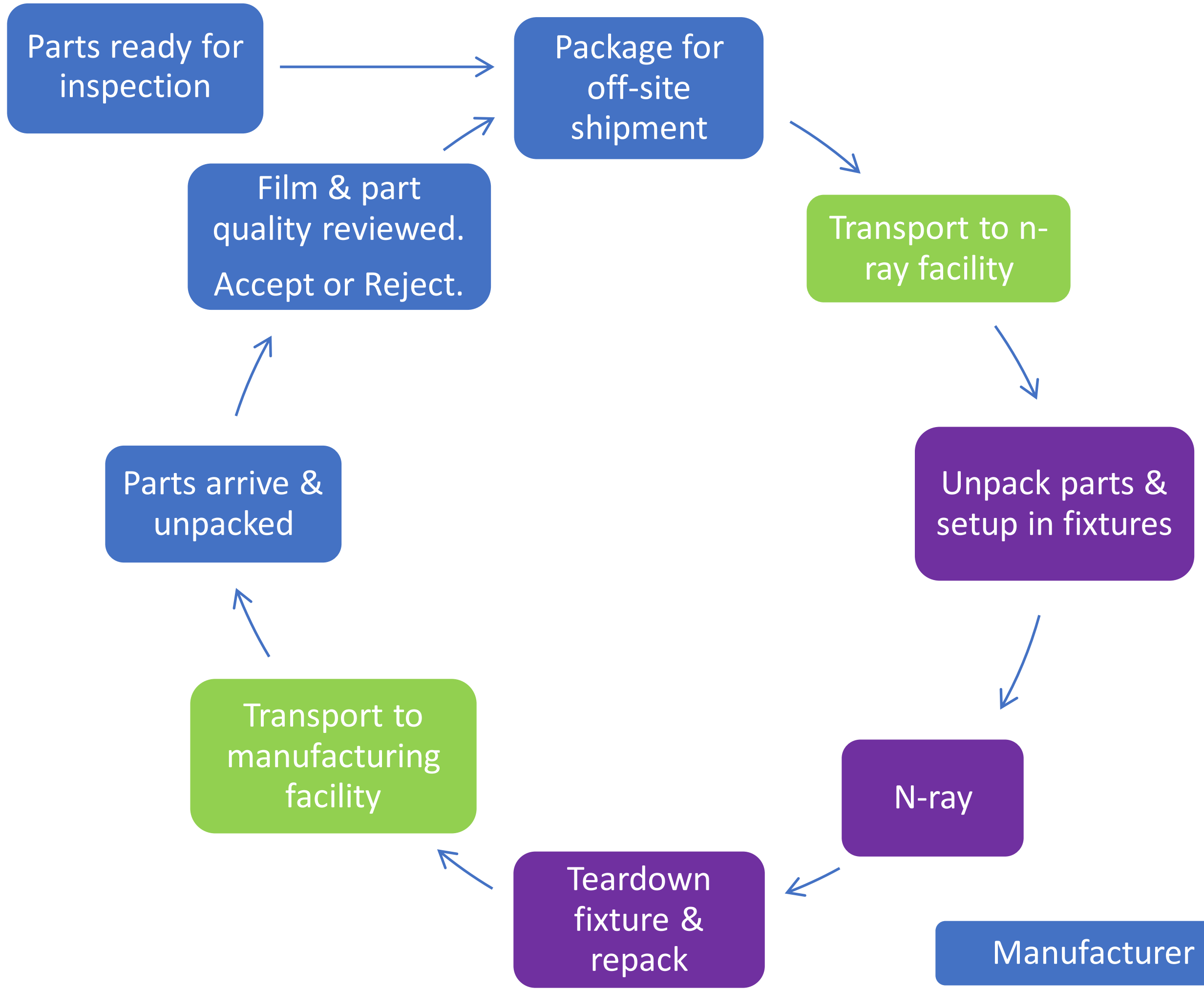
- Large caliber munitions, missiles and solid rocket motors
  - Need high penetration through thick metal cladding, warheads or fuel to view internal parts

- 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

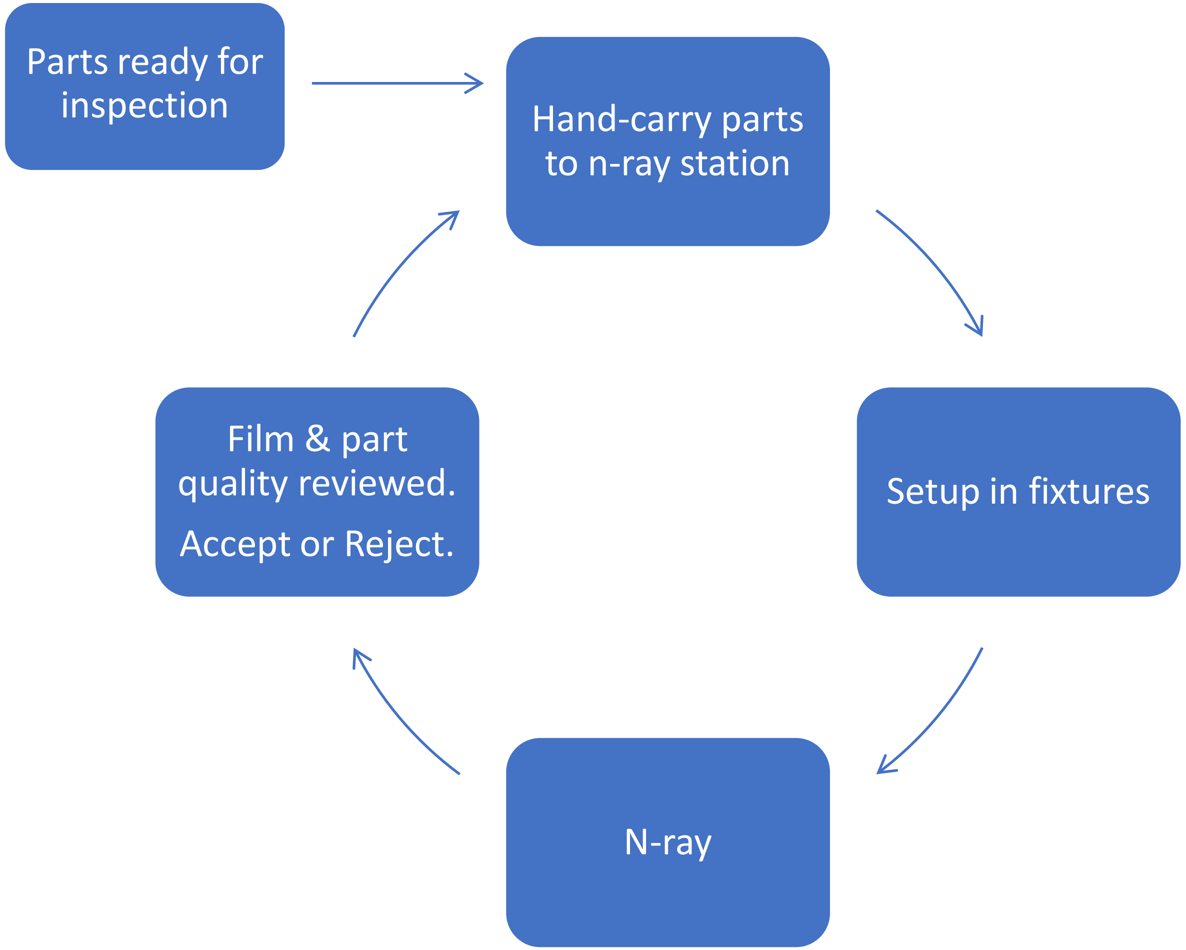
Reactor Based Radiography Cycle



- 1-2 week <u>typical</u> 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

Manufacturer possession | Transporter possession | N-ray Reactor possession

On-Site Accelerator Radiography Cycle



- 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

Manufacturer possession

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

PNIC Groundbreaking Ceremony October 30, 2018

PHOENIX

TRANSFORMING NUCLEAR TECHNOLOGY

Madison, WI

Brad.Bloomquist@PhoenixWI.com
www.PhoenixWI.com

608.210.3060