NAMP Young Investigators Series: Radioecology

Dawn Montgomery
Phillip Lyons
Delvan Neville
Meet the Presenters...

**Dawn Montgomery** is a Ph.D. student in Environmental Engineering and Earth Sciences at Clemson University working with Drs. Nicole Martinez and Brian Powell. Her academic and research emphasis is within the environmental health physics and radioecology disciplines. Currently, her research is centered on plant uptake of various radioactive contaminants and the associated role that plants have on the transport of those contaminants in the environment. Additionally, she is interested in dosimetric modeling of non-human biota and has developed several phantoms for the grass species used in her uptake experiments and stylized phantoms for an adult duck and a duckling. Montgomery earned a B.S. in Applied Mathematics from North Carolina State University in 2005. She expects to graduate in December 2019.

Contact Information: damontg@Clemson.edu
Presentation: **Uptake and dosimetric modeling of $^{99}$Tc, $^{133}$Cs, $^{237}$Np, and U in a native grass**
Uptake and dosimetric modeling of $^{99}\text{Tc}$, $^{133}\text{Cs}$, $^{237}\text{Np}$, and U in a native grass

Dawn Montgomery
Clemson University
Multiple Scales and Processes

Task A: Development of robust, high capacity waste forms (ceramic, glass, cementitious, native fuel forms)

Task B: Understanding the influence of coupled chemical, physical, and biological processes on radionuclide transport in the environment

Task C: and Imaging Facility: Upscaling from laboratory to field-scale systems: Field lysimeter experiments, pore scale imaging, and integrated monitoring systems

Task D: Reactive transport models predicting radionuclide release from an engineered system and transport through the environment

pm nm μm mm m km

Ion Interactions
Spatial Scaling
Biogenic Ligands
Redox Processes
Soil Sorption → Hydroponics → Plant-Soil Columns

Baseline $K_D$ and effects due to ligands

Uptake and dosimetry

Combining soil sorption and uptake

Montgomery et al 2017

Montgomery et al 2018

Nuclides of concern

- $^{99}$Tc, $^{237}$Np, $^{135}$Cs/$^{137}$Cs and U
  - Long-lived nuclides present in nuclear waste and potential spent fuel recycling streams
  - Expected to be mobile and potentially hazardous to human and environmental health
  - Complex biogeochemical behavior with different sorption mechanisms, redox activity, solubility, overall mobility, bioavailability, and analogous nature to plant nutrients

- Technetium(VII) as pertechnetate, $\text{TcO}_4^-$
  - Oxyanion, very weakly complexing, highly mobile

- Cesium, $\text{Cs}^+$

- Neptunium(V), $\text{NpO}_2^+$

- Uranium(VI), $\text{UO}_2^{2+}$
Plant Uptake Studies: Hydroponics & Columns
Main route followed by metal elements in plants

Metal ions are loaded into the xylem as free ions or conjugates.

Moving with water, ions are delivered to the shoot.

In the shoot, metal ions are subcellularly partitioned or detoxified.

A small portion of ions can cycled back to the root tissue.

DalCorso et al., 2014
Plant Uptake Motivation & Objectives

• Insight needed into potential plant mediated mechanisms of observed upward migration of radionuclides in soil columns.
  – *A. virginicus* is a common ground covering in the Southeastern US (and at Savannah River Site)
  – The suite of nuclides considered encompass a wide range of biogeochemical behavior

• Evaluate the propensity of *Andropogon Virginicus* to take up $^{99}$Tc, $^{133}$Cs (stable analog for $^{137}$Cs), $^{237}$Np and $^{238}$U
  – Interested in the effect of plant root exudates on the uptake and mobilization of radionuclides.
  – Working towards understanding radionuclide mobilization in soils as influenced by plant root foraging activities and microbial associations.
Hydroponic Experimental Set-Up

Acclimation
- 1 week laboratory acclimation
  - 16 plants (4 groups of 4)
  - 12 hour light cycle
  - Hoagland nutrient solution

Spiked Hydroponic Solution
- 3 spiked groups, 1 control (non-rad)
  - ~75 ppb $^{99}$Tc
  - ~10 ppb $^{237}$Np, $^{238}$U, & $^{133}$Cs

Harvest
- Harvest at 1, 3, and 5 days
- Roots rinsed and shoots separated
- One plant per group selected for autoradiography

Drying and Digestion
- Dried at 50 °C to a constant mass
- Bench top digestion with HNO$_3$/H$_2$O$_2$ (EPA 3050B)

Analysis
- Analysis of hydroponic solution and plant digestate via ICP-MS and LSC
Autoradiography of $^{99}$Tc uptake

- **Intensity** positively correlated with **growth time**
- **Root-shoot connection and/or shoot tips** appeared to have higher $^{99}$Tc content
- Seedlings/smaller plants used to investigate differences in uptake
Uptake - Concentration Ratios, $^{99}$Tc

- TcO$_4^-$ proposed to be associated with uptake mechanisms for:
  - SO$_4^{2-}$, MoO$_4^{2-}$, SeO$_4^{2-}$, NO$_3^-$, Cl$, PO_4^{3-}$

- **Plant part** is significant for established plants

- **Harvest day** is significant for seedlings

- **Plant age (experiment)** is significant

ANOVA analysis P-Values

<table>
<thead>
<tr>
<th>Factor</th>
<th>All Plants</th>
<th>Established</th>
<th>Seedlings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant Part</td>
<td>0.108</td>
<td>&lt;0.001</td>
<td>0.763</td>
</tr>
<tr>
<td>Harvest Day</td>
<td>0.006</td>
<td>0.071</td>
<td>0.030</td>
</tr>
<tr>
<td>Experiment</td>
<td>&lt;0.001</td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>

CR = \frac{C_{plant\ part}}{C_{HP\ solution}}

_Bennett and Willey, 2003; Cataldo et al., 1983; Robertson et al., 2003_
Uptake - Concentration Ratios, $^{133}$Cs

- Analogous to $K^+$
- Plant part is significant for established plants
- Harvest day is significant for seedlings
- Plant age (experiment) is significant

ANOVA analysis P-Values

<table>
<thead>
<tr>
<th>Factor</th>
<th>All Plants</th>
<th>Established</th>
<th>Seedlings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant Part</td>
<td>0.004</td>
<td>&lt;0.001</td>
<td>0.355</td>
</tr>
<tr>
<td>Harvest Day</td>
<td>0.075</td>
<td>0.738</td>
<td>0.007</td>
</tr>
<tr>
<td>Experiment</td>
<td>0.002</td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>

$$CR = \frac{C_{\text{plant part}}}{C_{\text{HP solution}}}$$
Uptake - Concentration Ratios, $^{237}$Np

- No nutrient analog
- Plant part and harvest day are significant
- Plant age (experiment) is significant

ANOVA analysis P-Values

<table>
<thead>
<tr>
<th>Factor</th>
<th>All Plants</th>
<th>Established</th>
<th>Seedlings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant Part</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Harvest Day</td>
<td>0.001</td>
<td>&lt;0.001</td>
<td>0.020</td>
</tr>
<tr>
<td>Experiment</td>
<td>&lt;0.001</td>
<td>***</td>
<td>***</td>
</tr>
</tbody>
</table>

$$CR = \frac{C_{\text{plant part}}}{C_{\text{HP solution}}}$$
Uptake - Concentration Ratios, $^{238}$U

- No nutrient analog
- **Plant part** is significant for both
- Harvest day is significant for established plants
- **Plant age** (experiment) is not significant

ANOVA analysis P-Values

<table>
<thead>
<tr>
<th>Factor</th>
<th>All Plants</th>
<th>Established</th>
<th>Seedlings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant Part</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Harvest Day</td>
<td>0.046</td>
<td>0.006</td>
<td>0.480</td>
</tr>
<tr>
<td>Experiment</td>
<td>0.105</td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>

$$CR = \frac{C_{\text{plant part}}}{C_{\text{HP solution}}}$$
Major findings: Hydroponic Studies

• Many radionuclides are readily incorporated into plants and the partitioning appears to be related to solubility, complexation affinity and similarity to plant nutrients.

• Concentration ratios vary by radionuclide, time of exposure, and plant part.

• Roots generally have higher concentration ratios, particularly for analytes without nutrient analogs, likely due to radionuclide sorption to the root vice true uptake.

• Plant size/age seems to have an influence on uptake
Soil Column Experiments (In Progress)

Transplant & Acclimation
- 50/50 SRS soil/sand (25 cm)
- A. virginicus seedlings transplanted (3-5 leaves)
- Irrigated (2-3 d), effluent collected

Spike Introduction
- Injection via Rhizon CSS© sampler at 7.6 cm depth
- ~1000 µg L⁻¹ ⁹⁹Tc
- ~100 µg L⁻¹ ¹³³Cs, ²³⁷Np, U

Shoot Harvest
- Shoots harvested at 4 weeks
- Columns covered & held at 5 °C until segmentation

Column Segmentation
- 1 cm thick transverse segments
- Separating roots from soil

Digestion & Analysis
- Plant & soil segments dried
- Digestion/leaching (EPA 3050B)
- Analysis via ICP-MS and LSC (⁹⁹Tc)
Dosimetric Model Development
Dosimetry Motivation & Objectives

- Establishment of appropriate protection standards requires sufficient knowledge of dose effects
  - Although organ-specific screening levels maybe impractical, considering only “whole body” (or above ground plant part) dose rates may not be adequately protective
- Dose determination
  - Direct measurement or robust dosimetric modeling
  - Lack of appropriate models results in occasional controversy: need refined and consistent dosimetric modelling approaches

- Describe the development, application, and comparison of dosimetric models utilized in the internal dosimetry of non-human biota
- Ultimate goal of this work is to combine refined dosimetric models with models describing temporal uptake in *A. virginicus* to obtain temporal dose rates
Current methodology

• Certain reference organisms applied to similar species
  – ICRP: 12 “Reference Animals and Plants”
  – ERICA tool: about 40 reference organisms
  – RESRAD-BIOTA: 4 reference organisms

• Dose rates approximated using dose conversion factors (DCFs)
  – Absorbed dose rate per unit activity concentration (µGy d⁻¹ per Bq kg⁻¹)

• Assumptions:
  – Uniform radionuclide distribution in organism or environmental media (representative conditions)
  – Ellipsoidal body, spherical organs (if included)
  – Decay properties of specific radionuclides
  – Monte Carlo based radiation transport codes
Computational models

- Incorporated into Monte Carlo based radiation transport computer codes for application in radiation dosimetry, as well as medical imaging simulation and evaluation.

Stylized phantoms
- Combinations of simple, equation-based surfaces for object representation

Voxel phantoms
- Objects represented by three dimensional voxel matrices

Hybrid phantoms
- Combination of stylized and voxel phantoms
  Utilize non-uniform rational B-spline surfaces (NURBS)

ICRU sphere

Image-based rigid 3D models

Deformable (variable posture) and moving (dynamic) 4D models

MIRD anthropomorphic models

Zaidi and Tsui 2009
Model Development

Stylized Phantom

Micro-CT of plant

Voxel Phantom: 3D Doctor

Hybrid Phantom: Rhinoceros 3D
Example Non-Human Phantoms

Some others: Mouse, Rat, Rabbit, Crab, Flat Fish, Honey Bee, Bee Hive, Pine, Arabidopsis thaliana

Stabin et al., 2015
Hybrid Beagle Phantoms

Martinez et al., 2016
Stylized, Voxel, Hybrid Trout

Fig. 1. Image of the male dog NURBS model (Rusty). Above, selected organs; below, selected skeletal segments.

Kinase, 2008
Voxel Frog Phantom

Montgomery et al., 2016
Stylized Duck and Duckling
Stylized Phantom

- **Roots (3):**
  - Cylindrical
  - 10 cm x 0.05 cm
  - immersed in water in a glass flask

- **Shoots (3):**
  - Elliptical cylinders
  - 18 cm x 0.2 cm x 0.05 cm
Voxel Phantom

Import micro-CT into 3D Doctor

Contour slices

3D Render

Verify geometry

Export to lattice tool
Voxel $\rightarrow$ NURBS (Hybrid) Phantom

Voxel Phantom  $\rightarrow$  Rhinoceros 3D  $\rightarrow$  Hybrid Phantom
Radiation Transport Simulation

• Monte Carlo
  – MCNP/MCNPX, EGS4, GATE, GEANT 4

• MCNP
  – Output is energy deposition (MeV) normalized per disintegration (*f8 tally)
  – Tally energy deposition in tissues of interest
  – Dose conversion factor × activity concentration = dose rate
  – Absorbed fractions (most commonly reported)

• Generally need supercomputer (Palmetto Cluster)
## Whole Plant DCF ICRP 108 Comparison

### External DCF

<table>
<thead>
<tr>
<th>DCF (µGy d⁻¹ per Bq kg⁻¹)</th>
<th>Cs-137</th>
<th>Tc-99</th>
<th>Np-237</th>
<th>U-238</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0E-08</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.0E-07</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.0E-06</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.0E-05</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.0E-04</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.0E-03</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.0E-02</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Internal DCF

<table>
<thead>
<tr>
<th>DCF (µGy d⁻¹ per Bq kg⁻¹)</th>
<th>Cs-137</th>
<th>Tc-99</th>
<th>Np-237</th>
<th>U-238</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0E+00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.0E+00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.0E+00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.0E+00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.0E+00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.0E+00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Note:**
- External (stylized)
- External (voxel)
- External (hybrid)
- External ICRP 108 (terrestrial)
- Internal (stylized)
- Internal (voxel)
- Internal (hybrid)
- Internal ICRP 108 (terrestrial)

~1 – 3 orders of magnitude difference

**geometry effects**

<0.3 order of magnitude difference

(~4% – 50% difference)

### DCF Calculation

\[
DCF \left( \frac{\mu \text{Gy day}^{-1}}{\text{Bq kg}^{-1}} \right) = \frac{\text{MeV}}{\text{disintegration}} \cdot \frac{\text{dis/sec}}{\text{Bq}} \cdot \frac{1.602 \times 10^{-13} \text{J}}{\text{MeV}} \cdot \frac{86400 \text{ s}}{\text{day}} \cdot \frac{\text{Gy}}{\text{J/kg}} \cdot \frac{10^6 \mu \text{Gy}}{\text{Gy}}
\]
External DCF Phantom Comparison

<table>
<thead>
<tr>
<th>Target Tissue</th>
<th>Phantom</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roots</td>
<td>Stylized → Voxel</td>
<td>34% - 55%</td>
</tr>
<tr>
<td></td>
<td>Voxel → Hybrid</td>
<td>17% - 32%</td>
</tr>
<tr>
<td>Shoots</td>
<td>Stylized → Voxel</td>
<td>8% - 52%</td>
</tr>
<tr>
<td></td>
<td>Voxel → Hybrid</td>
<td>2% - 31%</td>
</tr>
</tbody>
</table>
Greatest relative differences when source ≠ target due to root-shoot gap in stylized phantom.

Cs γ: 38% difference (stylized → voxel)
Most others < 10%
Combining uptake with DCF

**Internal Dose Rate: $^{99}$Tc, Hybrid Phantom**

- **Time (days):** 0, 2, 4, 6
- **Internal Dose Rate (µGy d$^{-1}$):** 0, 2, 4, 6
- **Symbols:**
  - roots: brown circle
  - shoots: green triangle

**External Dose Rate: $^{99}$Tc, Hybrid Phantom**

- **Time (days):** 0, 1, 2, 3, 4, 5, 6
- **External Dose Rate (µGy d$^{-1}$):** 0.00, 0.02, 0.04, 0.06, 0.08, 0.10, 0.12
- **Symbols:**
  - roots: brown circle
  - shoots: green triangle
Dosimetric Modeling Key Points

- Detailed dosimetric models provide higher fidelity and flexibility than traditional ellipsoid models, but some limitations remain
  - Looking for a **balance** between detail and resource requirements

- Normally dose rates from anthropogenic activities are low, although **screening values** have been exceeded
  - If screening values are exceeded, it may be helpful to consider a more detailed or realistic phantom

- Screening criteria are **not consistent** between countries and **no specific approach** exists for performing a detailed environmental impact assessment should a criteria be exceeded

- Recent international consideration has resulted in development of a **multi-part framework** for impact assessment
  - Includes undertaking progressively more refined assessments and improved models

*Smith et al 2010, Jackson et al 2014*
References

8. Martinez NE, Johnson TE, Pinder JE. Application of computational models to estimate organ radiation dose in rainbow trout from uptake of molybdenum-99 with comparison to iodine-131. Journal of Environmental Radioactivity 151: 468–479; 2016. DOI:10.1016/j.jenvrad.2015.05.021
Acknowledgements

Advisors: Drs. Nicole Martinez and Brian Powell
Committee Members: Drs. Dan Kaplan and Nishanth Tharayil
Nimisha Edayilam for providing plant specimens and assistance
Powell & Martinez research groups

This material is based upon work supported by the U.S. Department of Energy Office of Science, Office of Basic Energy Sciences and Office of Biological and Environmental Research under Award Number DE-SC-00012530 (uptake and student support) as well as the United States Nuclear Regulatory Commission Nuclear Education Grant #NRC-HQ-13-G-38-0002 (dosimetry and faculty support).

Clemson University is acknowledged for generous allotment of compute time on Palmetto cluster.
Fukushima’s Wildlife

Mammalian Species in and Around the Exclusion Zone

Phillip C. Lyons¹,²; Thomas G. Hinton³, Kei Okuda¹, Matt Hamilton¹,²; James C. Beasley¹,²

¹Savannah River Ecology Laboratory, ²Warnell School of Forestry and Natural Resources, ³Institute of Environmental Radioactivity
Roadmap

• Background

• Study area

• Methods

• Results
Background: Nuclear Accidents

- Three Mile Island
  - March 28, 1979
  - Level 5

- Chernobyl
  - April 26, 1986
  - Level 7

- Fukushima
  - March 11, 2011
  - Level 7
Fukushima Disaster

- Great East Japan Earthquake: magnitude 8.9
- Tsunami waves >40m (133 ft)
- 4 nuclear power plants damaged
- Fukushima Daiichi: 3 reactor meltdowns
Exclusion Zone

• Created on the day of the earthquake

• Maximum radiation: 91 μSv/hr

• 1150 km²

• 170-200k people evacuated
Study Area

- **120 locations**
  - **40 locations** per area/zone
- **60 cameras** deployed per each two-month iteration
  - **Red zone**: 10 upland, 10 lowland
  - **Green zone**: 10 upland, 10 lowland
  - **Control area**: 10 upland, 10 lowland
Trap Design

- Initial install dates: May 6-13, 2016
- Cameras placed ~ 60cm from base of tree along well-traveled trails
- Three-shot burst of photos per detection
- No quiet period between detections
Raw Data

- 14,400 camera days
- 268,961 images
- 1120 mean images per camera deployment
- 17 mammalian species
### Detections Per Species

- **Domestic Cat**: 1254
- **Red Fox**: 1277
- **Serow**: 1845
- **Badger**: 1904
- **Civet**: 2743
- **Raccoon**: 2863
- **Macaque**: 4118
- **Hare**: 6262
- **Raccoon Dog**: 7864
- **Boar**: 45160
Analysis

• Daily presence/absence design
• Utilized the R program UNMARKED for both occupancy and abundance
• Occupancy: Mackenzie et al. 2002 methods
• Abundance: Royle and Nichols 2003 methods

Covariates

• Vegetation
• Distance to water source
• Site microseiverts per hour
• Distance to nearest road
• Human trail usage
• Zone
• Elevation
Serow

*Capricornis crispus*
Wild Boar
Sus scrofa
Wild Boar
Sus scrofa

**Boar Occupancy**
- Control
- Green
- Red

**Boar Abundance**
- Control
- Green
- Red
Raccoon Dog

*Nyctereutes procyonoides*

**Occupancy**

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>Green</th>
<th>Red</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occupancy</td>
<td>0.68</td>
<td>0.74</td>
<td>0.72</td>
</tr>
</tbody>
</table>

**Abundance**

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>Green</th>
<th>Red</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abundance</td>
<td>2.5</td>
<td>1.5</td>
<td>1.0</td>
</tr>
</tbody>
</table>
Discussion

• Occupancy higher in exclusion zone for 6 of 9 species
  • Pig, Macaque, Raccoon, Badger, Hare, Raccoon Dog)
• Abundance higher in exclusion zone for 6 of 9 species
  • Pig, Macaque, Raccoon, Civet, Fox, Hare
• Human presence may have the strongest impact on area wildlife occupancy and abundance
• Radiation exposure has minimal impact on area wildlife occupancy and abundance
Acknowledgements

• Matt Hamilton
• Dr. Tom Hinton
• Dr. Kei Okuda
• Hannah Gerke
• Dr. James Beasley
Questions?
Discount Albacore Radioecology: Hunting Cs-137 on a budget

Delvan R. Neville
Oregon State University
US Pacific albacore

- Primarily long-line trolling
- Fishery took off ca. 1915 @ 20,000,000 lbs/yr
- 3rd largest gross $ in Oregon
  - Behind Dungeness crab & Pink shrimp
- Open fishery – No catch limits
2009 Troll & Pole Catch

Childers & Pease, 2012
Dried isn’t enough!
No funds! What to dry ash in?
This won’t do
Stainless steel?
Wear & tear & K-40
EXTREME WORKING TEMPERATURE
EXTREME WORKING TEMPERATURE
“Hottest” to date: <2 Bq/kg ww
Preliminary Results - Cs-137
Preliminary Results - Cs-137
Preliminary Conclusions

• Food safety?
  – No issue

• Different populations?
  – Larger sample size needed -> Future work
  – Adjust for PDO & ENSO

• Dose impact?
  – Likely minimal, but opportunity to plan for larger oceanic release -> Future work
Dose in Pacific albacore

- ICRP Reference trout & flatfish
  - Neither perfect surrogate
  - Officially both ellipsoids
- Voxel models
  - Presumed more accurate
  - Time intensive
Voxel models - Variable accuracy
Imaging Albacore - Too big!
Stitch 3D medical images?
Stitch 3D medical images
References

- Ichinokawa et al. 2008. Transoceanic migration rates of young North Pacific albacore, Thunnus alalunga, from conventional tagging data. Canadian Journal of Fisheries and Aquatic Sciences 65: 1681-1691
Acknowledgements

- Kathryn Higley
- Jason Phillips
- Oregon Sea Grant
- Newport albacore fishing community
Questions for our presenters??
Upcoming Webinars

- Young Investigators Series: Novel Uranium Nanostructures
- Radiopharmaceutical Series: The History of Nuclear Medicine and Radiopharmaceuticals
- Radiopharmaceutical Series: Basics of Radiochemistry for Radiopharmaceuticals/Target, Ligand, Chemistry and Radiochemistry

NAMP website http://www.wipp.energy.gov/namp/