Radiation Protection in the 21st Century – a Look at the Turning Points in the Practice of Radiation Protection to Envision the Future

For the CIRMS 2019 Conference: Strengthening the Economy and Homeland Security with Radiation Measurements and Standards

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National Institute of Standards and Technology
Gaithersburg, MD
Disclaimer

The views and opinions expressed herein do not necessarily state or reflect those of the United States Government or any agency or Contractor thereof.
It's hard to make predictions, especially about the future.

*Niels Bohr*
Prescient  [presh-uh nt]

adjective
having prescience,
or knowledge of things or events before they exist or happen; having foresight:
*The prescient economist was one of the few to see how successful hydraulic fracturing would become in driving the price of natural gas to all time lows.*

(adapted from Dictionary.com)
Turning Points in the Practice of Health Physics

What did I review?


• Reflection of my own experiences in the practice of Health Physics
  Cloutier (81); Neff & Simek (82); Zinn, Roach, & Turner (83-86), Tuttle & Remley, Fleissner, (86-89), Turner, Miller (89-), Zombori, Andras, Koblinger (90); Schultz, Hensley, Auxier, Sims, Holland, Muckenthaler, Rao, Ahmed, Halliburton, Anderson, Hopper, McLaughlin, Koskello, McElroy, Croft, Bowen, Hertel, Abelquist, Ansari, Pickett, Blumenthal
Area IV, Santa Susana Field Laboratory, Rocketdyne

KFKI, Budapest Hungary

$10MW_t$, $H_2O$ moderated, Be-reflected BRR
Oak Ridge National Laboratory
Formerly with 13 Operating Reactors, Isotope Separation Facilities

The world's oldest reactor achieved criticality at about 5:00 A.M. EWT (Eastern War Time), loading 31 tons of natural uranium slugs into 357 tubes in just over 12 hours!
A. Weinberg and J. Gillette show up to teach us M
The Health Physics Research Reactor (HPRR)
The Bulk Shielding Reactor (BSR)

From: Peretz, Fred (retired, ORNL)
The Oak Ridge Research Reactor

From: Peretz, Fred (retired, ORNL)
The Oak Ridge Research Reactors – Operational Summary

From: Rosenthal, 2014
<table>
<thead>
<tr>
<th>ORNL reactors</th>
<th>First critical</th>
<th>Highest power</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1940s</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oak Ridge Graphite Reactor (X-10, OGR)</td>
<td>November 4, 1943</td>
<td>3.5 MW</td>
</tr>
<tr>
<td><strong>1950s</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low-Intensity Test Reactor (LITR)</td>
<td>February 1950</td>
<td>3 MW</td>
</tr>
<tr>
<td>Bulk Shielding Reactor (BSR)</td>
<td>December 17, 1950</td>
<td>1 MW</td>
</tr>
<tr>
<td>Homogeneous Reactor Experiment (HRE-1)</td>
<td>April 15, 1952</td>
<td>1.5 MW (brief)</td>
</tr>
<tr>
<td>Tower Shielding Reactor (TSR)</td>
<td>March 12, 1953</td>
<td>500 kW</td>
</tr>
<tr>
<td>Aircraft Reactor Experiment (ARE)</td>
<td>November 3, 1954</td>
<td>1 up to 2.5 MW</td>
</tr>
<tr>
<td>Homogeneous Reactor Test (HRT or HRE-2)</td>
<td>December 27, 1957</td>
<td>5 MW</td>
</tr>
<tr>
<td>Oak Ridge Research Reactor (ORR)</td>
<td>March 21, 1958</td>
<td>30 MW</td>
</tr>
<tr>
<td>Pool Critical Assembly (PCA)</td>
<td>1958</td>
<td>10 kW</td>
</tr>
<tr>
<td>Aircraft Shield Test Reactor (ASTR)</td>
<td>(Pratt &amp; Whitney)</td>
<td>1 MW</td>
</tr>
<tr>
<td><strong>1960s</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tower Shielding Reactor II (TSR-II)</td>
<td>March 26, 1960</td>
<td>1 MW</td>
</tr>
<tr>
<td>Health Physics Research Reactor (HPPR)</td>
<td>1961</td>
<td>Burst</td>
</tr>
<tr>
<td>Molten Salt Reactor Experiment (MSRE)</td>
<td>June 1, 1965</td>
<td>8 MW</td>
</tr>
<tr>
<td>High-Flux Isotope Reactor</td>
<td>August 25, 1965</td>
<td>100 MW</td>
</tr>
<tr>
<td>Bulk Shielding Reactor modified (BSR-II)</td>
<td></td>
<td>2 MW</td>
</tr>
<tr>
<td>TSF-SNAP</td>
<td>April 7, 1967</td>
<td>10 kW</td>
</tr>
<tr>
<td><strong>Never operated</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aircraft Reactor Test (ART)</td>
<td></td>
<td>60 MW</td>
</tr>
<tr>
<td>Experimental Gas-Cooled Reactor (EGCR)</td>
<td></td>
<td>23 MW(e)net</td>
</tr>
<tr>
<td>Clinch River Breeder Reactor Project (CRBRP)</td>
<td></td>
<td>380 MW(e)</td>
</tr>
</tbody>
</table>

From: Peretz, Fred
ORNL Critical Experiments

From: A. D. Callihan, “Critical Experiments and Nuclear Safety at ORNL,” ORNL-2087, 1956
Building 9213 (1950-1973)

Also, Priv Comm: Calvin Hopper (Joe Thomas)
Turning Point #1: Waning Nuclear Infrastructure

- By the end of the 1990s – half-way through my career – we see a significant decline in supporting infrastructure for nuclear power, nuclear research, nuclear fuels, advanced reactors, and in fact, advanced detection methods, accelerator design and development.

- Focus was squarely on D&D.

- Health and Safety Research Division and Environmental Sciences Division staff declined from ~ 900 to less than 200, in a matter of 10 years.

- Waste Management, Chemical Technology, Reactor divisions saw a similar attrition of personnel.

- Result:
  - Recent graduates in the Nuclear Sciences entering the Department of Energy Laboratory system from the mid 1990s to 2010 found little to do, other than computing. At UTK, graduate students numbered in the 10s.
Lost Skillsets and Experience to Solve Challenging Health Physics-Related Problems

- Actinide Chemistry and Management
  - Contamination Control and Monitoring
  - Air Handling, Filtering, Sampling, and Monitoring
  - Waste Management
  - Packaging and Transport of Product and Waste
  - Internal Dosimetry
  - External Dosimetry (photon, beta, neutron)
  - Nuclear Safety (DSA)
  - Criticality Safety (NCSE)
  - Analytical Sampling and Analysis Methods Development (bioassay, product)
  - In-vivo and in-vitro bioassay methods
  - NonDestructive Assay (NDA)
  - Pathways Analysis
  - Shielding Design and Fabrication (irradiated targets, dissolution, extraction)
  - Effluent Monitoring and Environmental Monitoring
  - Emergency Response
  - Dose Reconstruction
  - No Rad Added of Mixed Wastes
  - Target Recovery (in Rabbit Pneumatic Systems)
Lost Skillsets and Experience to Solve Challenging Health Physics-Related Problems

- **Reactor Operation**
  - Shielding Design, Fabrication (Streaming Measurements)
  - Process Monitoring (Effluents, Environmental)
  - Fresh Fuel Management
  - Spent Fuel Management
  - Criticality Safety – spent fuel pool (High-density Rerack)
  - Contamination Control
  - Accident Analysis
  - Neutron Activation
  - Neutron dosimetry (TEPC chambers, Bonner Spheres, Long Counters)
  - Reactor Physics and Control
    - delayed critical, HFIR, ORR, BSR
    - prompt critical, HPRR
  - Measurement Sciences
Lost Skillsets and Experience to Solve Challenging Health Physics-Related Problems

- **Fuel Fabrication and Enrichment**
  - Criticality Safety
  - Criticality Accident Alarm Systems
  - Accident Dosimetry
  - Internal Dosimetry
  - **Analytical Measurement Methods Development**
    - **DA**
    - **NDA**
  - Nuclear Safety
  - Handling and Management of HEU (security, safeguards, safety)
  - Handling and Management of Plutonium (security, safeguards, safety)
  - Monitoring for contaminants (fixed, removable, airborne) and monitoring for holdup

Quality of radioactivity measurements is imperative (Tc-99, TRU, U232)
What did we do to address this “Turning Point”


- Davis and Dewji et. al. organized a workshop, titled “Radiation Protection Research Needs”, June 5-6, 2017

Available at: [https://info.ornl.gov/sites/publications/Files/Pub102365.pdf](https://info.ornl.gov/sites/publications/Files/Pub102365.pdf)
## Key HP Research Needs Identified (Dewji, et. al.)

<table>
<thead>
<tr>
<th>New Fuel Cycles/Reactors</th>
<th>Dosimetry/Risk</th>
<th>Medical Physics</th>
<th>Instrumentation and Operations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comparison of dose impact to existing cycles</td>
<td>Improvement of radiation risk estimates from biological data</td>
<td>Improve methods for calculating dose and corresponding risk of radiogenic cancer</td>
<td>Improved neutron instrumentation</td>
</tr>
<tr>
<td>Modeling and planning for radiological emergencies</td>
<td>Determination of cancer risk due to exposures at low dose</td>
<td>Develop methods for personalized radiation dose and risk calculations suitable for clinical applications</td>
<td>Indoor position logging</td>
</tr>
<tr>
<td>Waste handling and disposal</td>
<td>Personalization of dosimetry in medical applications</td>
<td>Improve methods for calculating dose and corresponding non-cancer late effects</td>
<td>Improved field-appropriate spectroscopy</td>
</tr>
<tr>
<td>Variation in environmental pathways</td>
<td>Rapid and accurate dose assessment during radiological emergencies</td>
<td>Improve simulation methods to model advanced-, emerging-, and next-generation radiation therapy and imaging technologies</td>
<td>Combination (radiological and chemical) detectors</td>
</tr>
<tr>
<td>Incorporation of new shielding technologies into reactor design</td>
<td>Refinement of the use of theoretical dose concepts and quantities</td>
<td>Definition and pathway for</td>
<td>Direction-specific detectors</td>
</tr>
<tr>
<td></td>
<td>Enhancement of radiation measurement systems</td>
<td></td>
<td>Improvement to instrument ruggedness</td>
</tr>
<tr>
<td></td>
<td>Development of environmental dosimetry for non-human biota</td>
<td></td>
<td>Instrumentation that can detect alpha, beta, neutron, and gamma radiation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Development of instruments that are hardened against radiation damage</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Definition and pathway for Very Low Level Waste</td>
</tr>
</tbody>
</table>

## Key HP Research Needs Identified (Dewji, et. al.)

<table>
<thead>
<tr>
<th>Space Radiation</th>
<th>National Defense</th>
<th>Emergency Response</th>
<th>Environmental Modeling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimization of shielding thickness</td>
<td>Determination of protection factors for vehicles and structures</td>
<td>Atmospheric dispersion modeling</td>
<td>Radionuclide fate and transport modeling</td>
</tr>
<tr>
<td>Secondary radiation produced in shielding</td>
<td>Improved radiation transport codes that allow incorporation of CAD data</td>
<td>Contaminant migration modeling</td>
<td>Incorporation of sport hunting and wild plant foraging in pathway models</td>
</tr>
<tr>
<td>Cross sections for heavy, energetic particle interactions</td>
<td>Biodosimetry for rapid triage</td>
<td>Population dose estimation</td>
<td>Identification of indicator species within each climatological area</td>
</tr>
<tr>
<td>Comparative dose response studies</td>
<td>Dosimetry models for combat animals</td>
<td>Dose assignment for emergency response workers</td>
<td>Confounding effects due to chemical and physical stressors in conjunction with radiological exposures</td>
</tr>
<tr>
<td>Individual, genetic-based risk profiles</td>
<td>Personnel performance degradation from medical countermeasures</td>
<td>Biodosimetry for rapid triage</td>
<td>Determination of biological effects risk due to exposures at low dose</td>
</tr>
<tr>
<td>Central nervous system damage effects</td>
<td>Development of coatings that inhibit contamination due to fallout</td>
<td>Improved bioassay for alpha emitters</td>
<td></td>
</tr>
<tr>
<td>Radiogenic cardiovascular effects</td>
<td>Portable, rugged detection instrumentation</td>
<td>Assay for low-energy contaminants</td>
<td></td>
</tr>
<tr>
<td>Low dose rate effects from all (incl. heavy) ions</td>
<td>Unmanned detection robots</td>
<td>Post-event decontamination</td>
<td></td>
</tr>
<tr>
<td>Improved astrophysical models to minimize dose based on mission timing</td>
<td>Urban plume modeling</td>
<td>Urban environment activation</td>
<td></td>
</tr>
<tr>
<td>On-site construction of shielding</td>
<td>Hardening of electronics against radiation damage</td>
<td>Directional radiation detectors</td>
<td></td>
</tr>
</tbody>
</table>

Let’s Look at Content of Papers Presented at HPS Annual Meetings, 2005 versus 2015

Experimental and Applied vs. Modelling and Computational
HPS 2015 Annual Meeting Program. **INFRASTRUCTURE AND EXPERIMENTATION:** Environmental Monitoring, Internal and External Dosimetry, and Medical Dosimetry

(Reference: Joseph Dirsa, ORNL Summer Intern)
HPS Annual Meeting Papers Infrastructure, 2005

- Dose Reconstruction: 13%
- Environmental Monitoring: 19%
- Internal/External Dosimetry: 15%
- Emergency Resp./Homeland Sec.: 24%
- Decontam./Decommis.: 9%
- Medical Health Physics: 9%
- NESHAPS: 11%
Examining the 2005 and 2015 HPS conferences, the amount of experimental/hands on work has seen a 12% decrease since 2005 (Reference: Joseph Dirsa, ORNL Summer Intern)
Turning Point #2: Technology Development – In-Situ Gamma-Ray Spectrometry

- In-situ Gamma-Ray Spectrometry, Melton Valley Storage Tanks, 1992
Turning Point #2: Technology Development – In-Situ Gamma-Ray Spectrometry

- **Physics Methods**
  - Computation Methods for Radiation Transport
    - Energy Dependent Source-to-Detector Radiation Transport
    - Detector Response functions
    - 1980s-1990s: point-kernel, or MCNP runs
    - 1995-present day: ISOCS or Program Isotopic

- Calibration ensures that we have matched the detector response to the source term of interest, for the “measured and unknown” material. **EMPIRICAL Tests**
Emergence of HPGe-based (transportable) In-situ Systems


Note: While these systems may look similar, the methodologies are significantly different.
Turning Point #2: Technology Development Driven By Ruggedized Computing Power, and Nuclear Electronics

- *Pulsed Neutron Differential Die-Away Systems*
Turning Point #2: Technology Development- Active Neutron Interrogation (1984-1999)
Turning Point #2: Technology Development –
Segmented Gamma-Ray Spectrometry (SGS), and
Tomographic Spectrometry Scanning (TGS)

ORNLS System- 1989
(Chapman, Schultz, Gillespie)

Commercial System- 2011
(Canberra Industries)
Turning Point #2: Technology Development - Computational Modelling Supplements Calibration, Test and Evaluation of NDA Systems for WIPP TRU Waste
### Table 1. NDA PDP activity ranges and associated scoring acceptance criteria.

<table>
<thead>
<tr>
<th>Activity range</th>
<th>Range of sample activity in $\alpha$-curies(^a)</th>
<th>Maximum Measured Precision(^b)</th>
<th>Bias Range(^c) (%R, and %RSD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>&gt; 0 to 0.02</td>
<td>14</td>
<td>Non-interfering matrix (%RSD)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Interfering matrix (%RSD)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lower: 70</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Upper: 130</td>
</tr>
<tr>
<td>Mid-Low</td>
<td>&gt; 0.02 to 0.2</td>
<td>10.5</td>
<td>Non-interfering matrix (%R)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Interfering matrix (%R)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lower: 70</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Upper: 130</td>
</tr>
<tr>
<td>Mid-High</td>
<td>&gt; 0.2 to 2.0</td>
<td>7</td>
<td>Non-interfering matrix (%R)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Interfering matrix (%R)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lower: 70</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Upper: 130</td>
</tr>
<tr>
<td>High</td>
<td>&gt; 2.0</td>
<td>3.5</td>
<td>Non-interfering matrix (%R)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Interfering matrix (%R)</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Lower: 70</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Upper: 130</td>
</tr>
</tbody>
</table>

\(^a\) Applicable range of TRU activity contained in a PDP sample; units are curies of alpha-emitting TRU isotopes with half-lives greater than 20 years.

\(^b\) Measured precision that must be met to satisfy the precision criteria at the 95% upper confidence bound, based on six replicates. The values are one relative standard deviation referenced to the known value for the test.

\(^c\) %R\(_L\) and %R\(_U\) values used in Equation 3 to determine the 95% confidence bound for the ratio of the mean of the measured values to the known value, expressed as a percent.

%R = percent recovery

%RSD = percent relative standard deviation
Turning Point #2: Technology Development – Calibration, Test, and Evaluation of Uncertainty (Implementation of GUM)

How do the characteristics of the standards effect the neutron based measurements?

- Mass – Used as standard
- Enrichment/Isotopics – Used for calculation of $^{235}\text{U}$ or $^{240}\text{Pu}_{\text{eff}}$
- Uniformity – not a big effect
- Grain size – not a big effect, may slightly change multiplication
- Impurities – production of (α,n) neutrons, can lead to large bias
- Moisture Content – moderation of neutrons, changes efficiency, additional (α,n) neutrons
- Chemical Form – production of (α,n) neutrons, multiplication
- Geometry – changes multiplication
- Density – changes multiplication
- Container design – negligible effect for passive measurements, can effect active measurements.
Turning Point #2: Technology Development – In-Situ Gamma-Ray Spectrometry (Low and Mid-Resolution)
Turning Point #3: Hands-On Training

8 HEU shells (93.2%)

93.2% HEU metal foils

α-phase Pu, poly refl.

From: DOE NNSA NCSP Training and Education Courses" Sedat Goluoglu, Course Coordinator, 2013 NCSD Topical Meeting, Wilmington, NC, October 1, 2013
Turning Point #3: Hands-On Training

Google

PTP Radiation Safety & Health Physics Training

NCERC NCSP LLNL
Summary

• **Nuclear Infrastructure**
• **Technology Development**
  – Data acquisition
  – Methods
• **Hands-on Training**

• **For the Future**
  – Application of Neural Networks/AI to large data sets
  – Big Data
  – Additive Manufacturing
  – Advanced Computational Methods
  – Smart Information/Data Management for Dosimetry, Measurement and Display of Radiological Data
  – Integration of Safety-Security-Safeguards