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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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

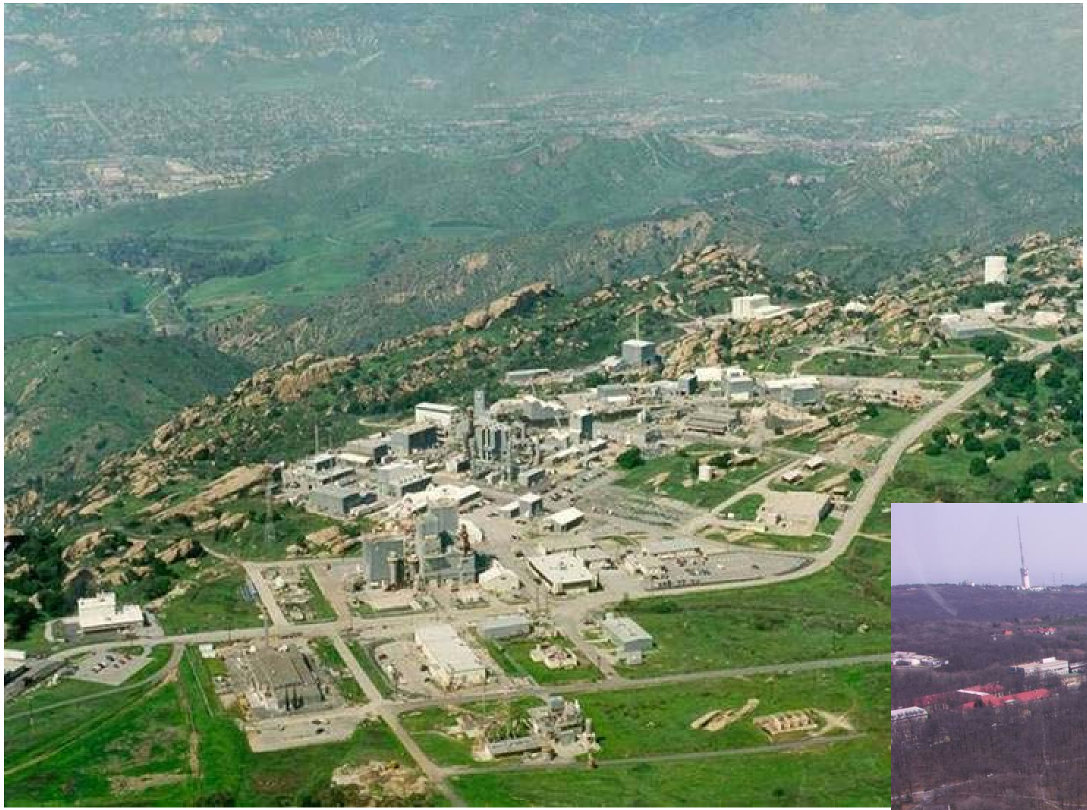
What did I review?

- Proceedings of the Health Physics Society, First Annual Meeting, University of Michigan, June 25-27, 1956

- Kathren, Higby, and McKinney, "Computer Applications in Health Physics," Proceedings of the 17th Midyear Topical Symposium of the Health Physics Society, 1984

- 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, Andrasi, 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

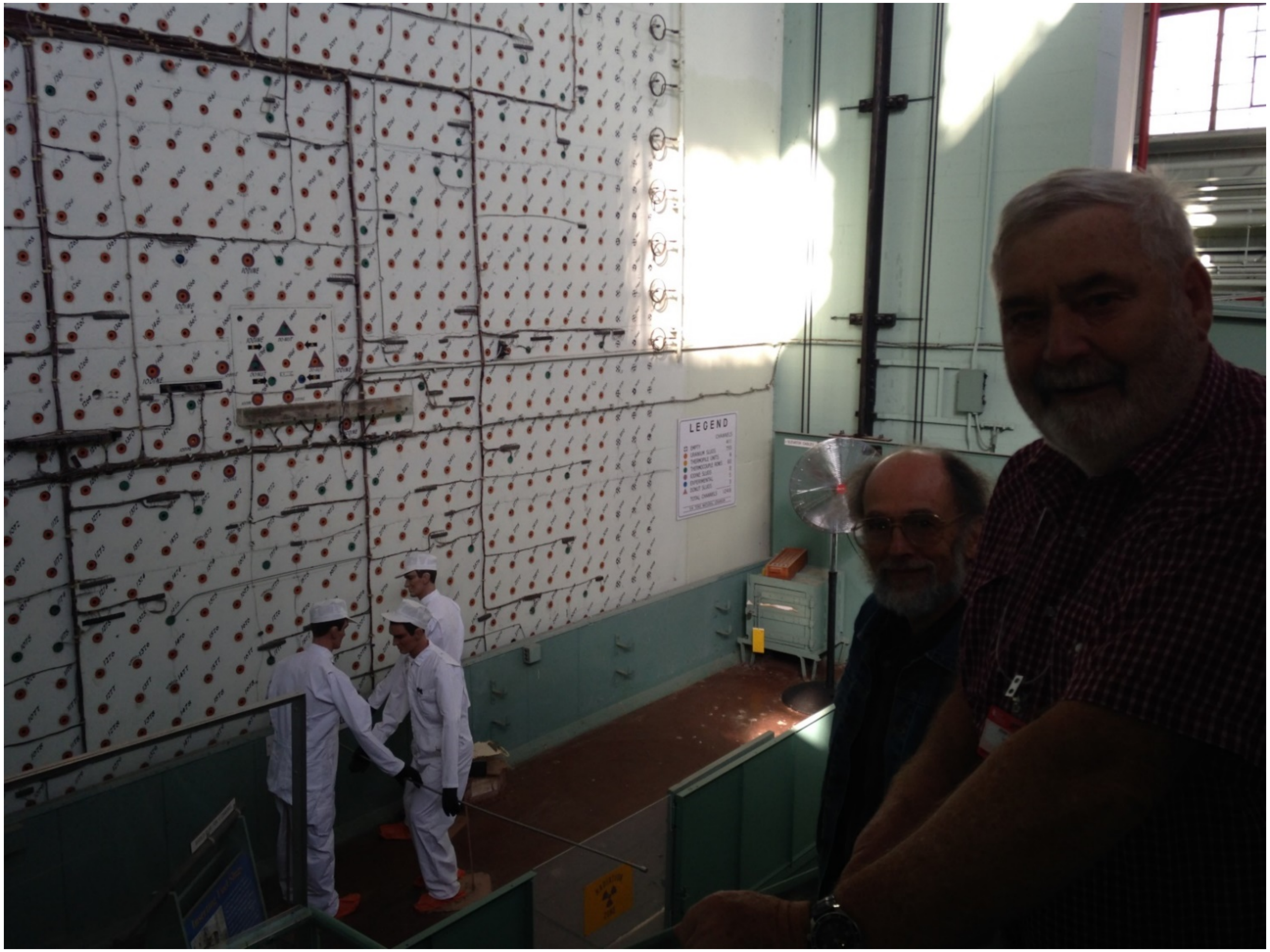
$10MW_t$, H_2O moderated, Be-reflected BRR

Oak Ridge National Laboratory

Formerly with 13 Operating Reactors, Isotope Separation Facilities

(Reference: Rosenthal, Murray "An Account of Oak Ridge National Laboratory's Thirteen Nuclear Reactors," 2009)

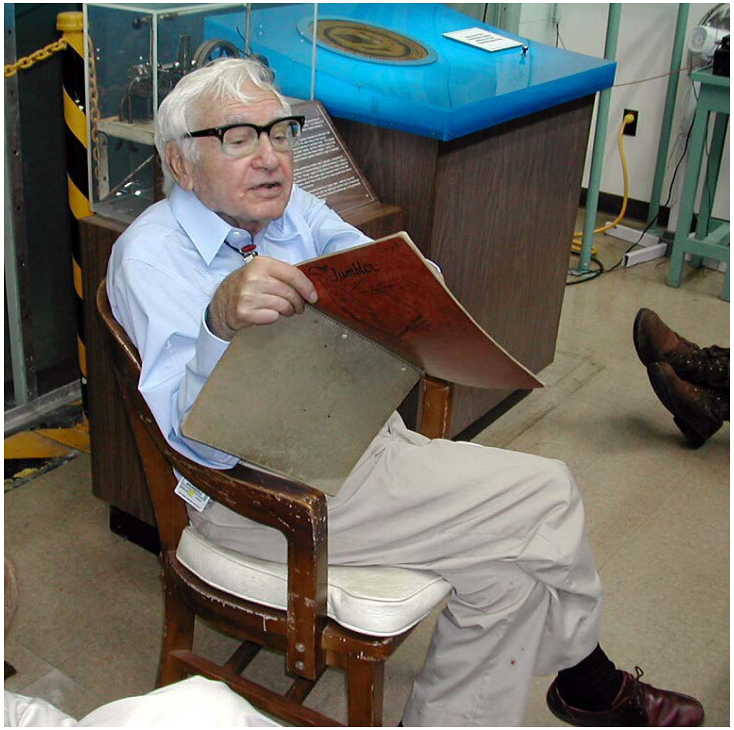
The Graphite Reactor (Initial Chain Reaction: 11/4/1943)



(Paul Frame and John Campbell, 2014.
Reference: John Campbell, “Rutherford”)

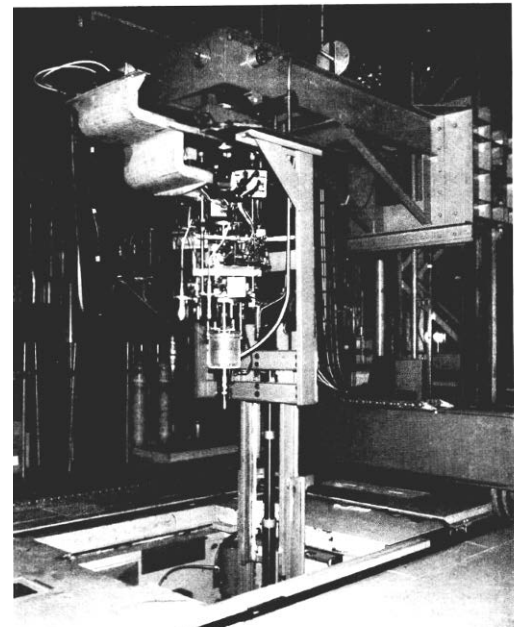
The world's oldest reactor achieved criticality at about 5:00 A.M. EWT (Eastern War Time), loading 31 tons of natural uranium slugs into 357 tubes in just over 12 hours!

A. Weinberg and J. Gillette show up to teach us M

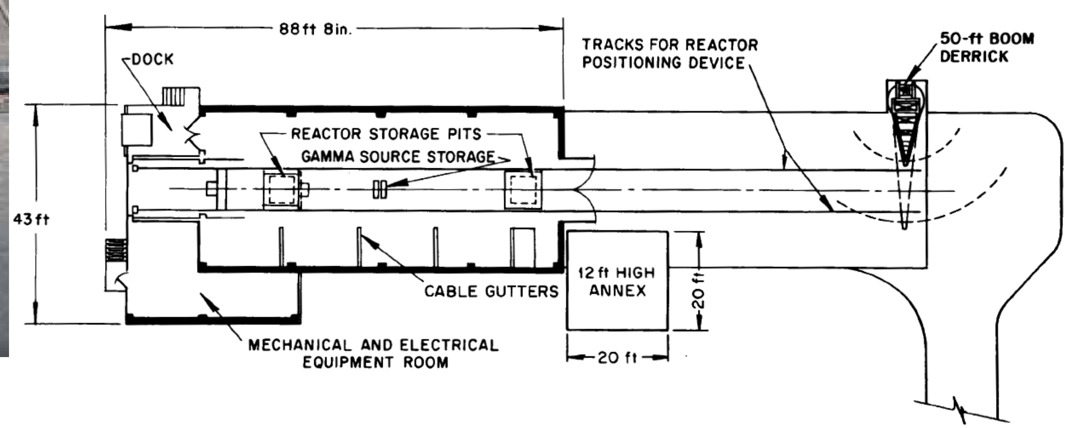


The Health Physics Research Reactor (HPRR)

ORNL-PHOTO 3749-85

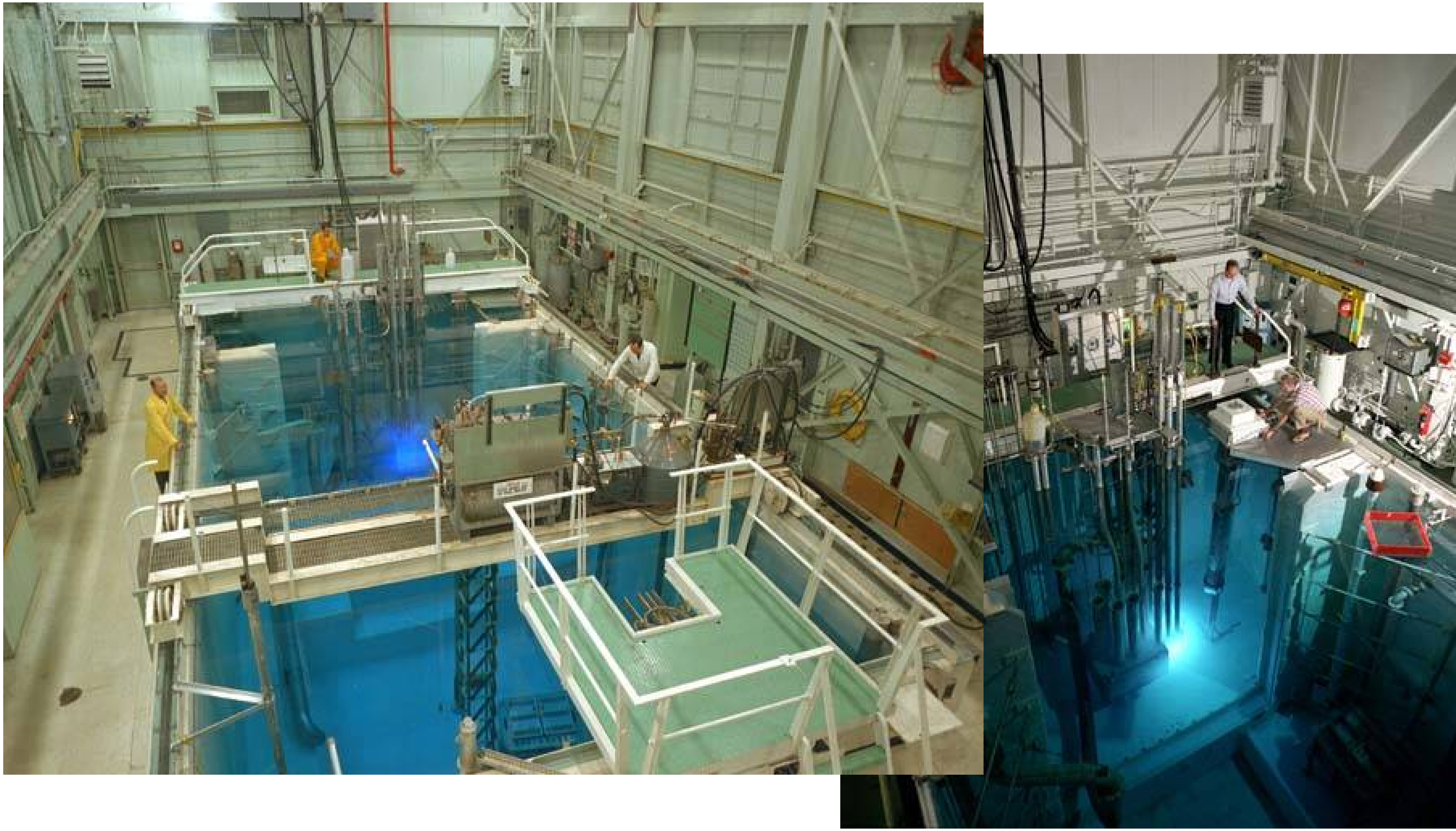


ORNL-LR-DWG 51249R2



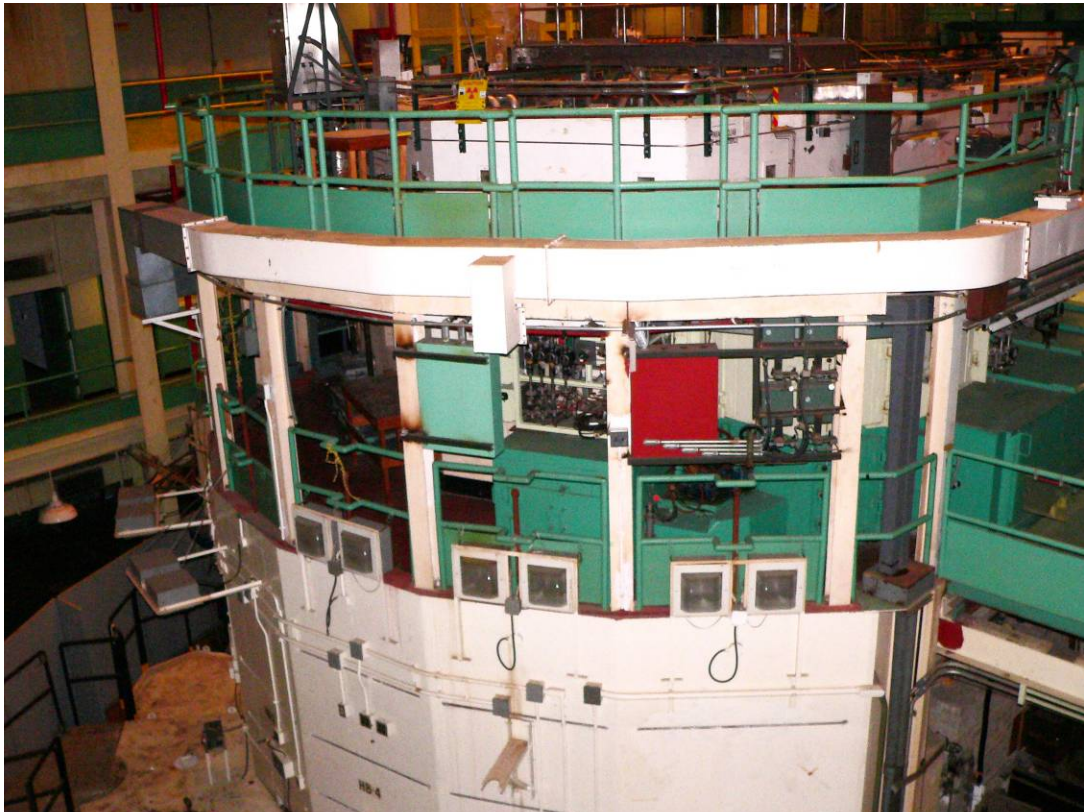
From: Peretz, Fred (retired, ORNL)

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

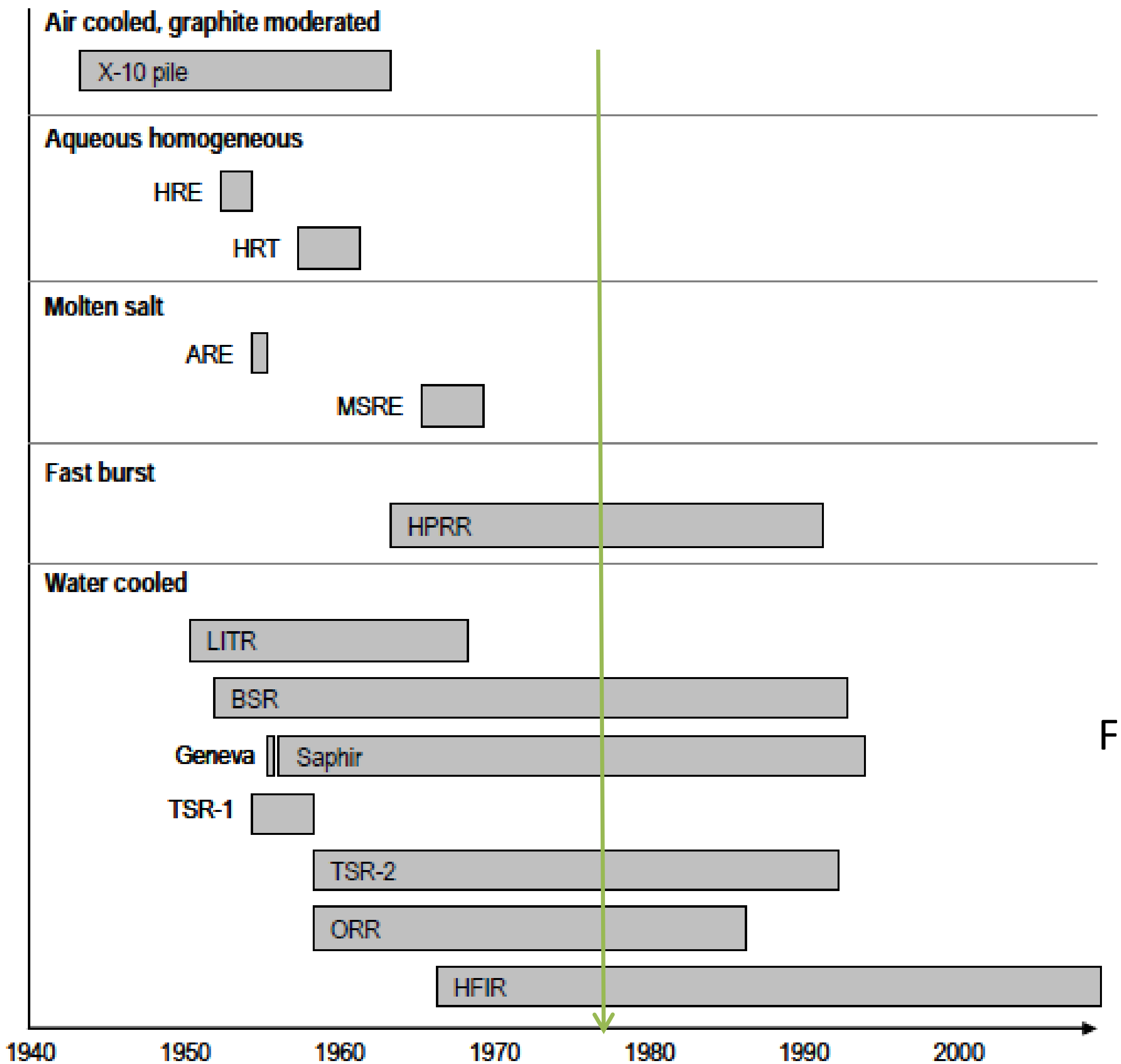


Fig. 9. ORNL's nuclear reactors, from criticality to shutdown.

From: Rosenthal, 2014

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

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

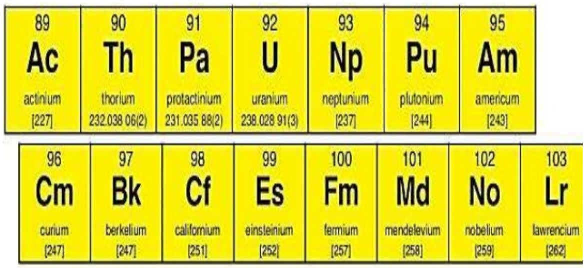
- *By the end of the end of the 1990s – half-way through my career – we see a significant decline in supporting infrastructure for nuclear power, nuclear research, nuclear fuels, advanced reactors, and in fact, advanced detection methods, accelerator design and development.*
- *Focus was squarely on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

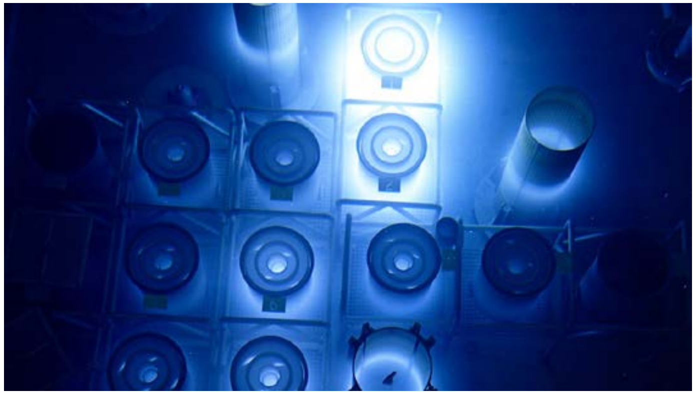
- *Actinide Chemistry and Management*
  - *Contamination Control and Monitoring*
  - *Air Handling, Filtering, Sampling, and Monitoring*
  - *Waste Management*
  - *Packaging and Transport of Product and Waste*
  - *Internal Dosimetry*
  - *External Dosimetry (photon, beta, neutron)*
  - *Nuclear Safety (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)*

Actinide



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

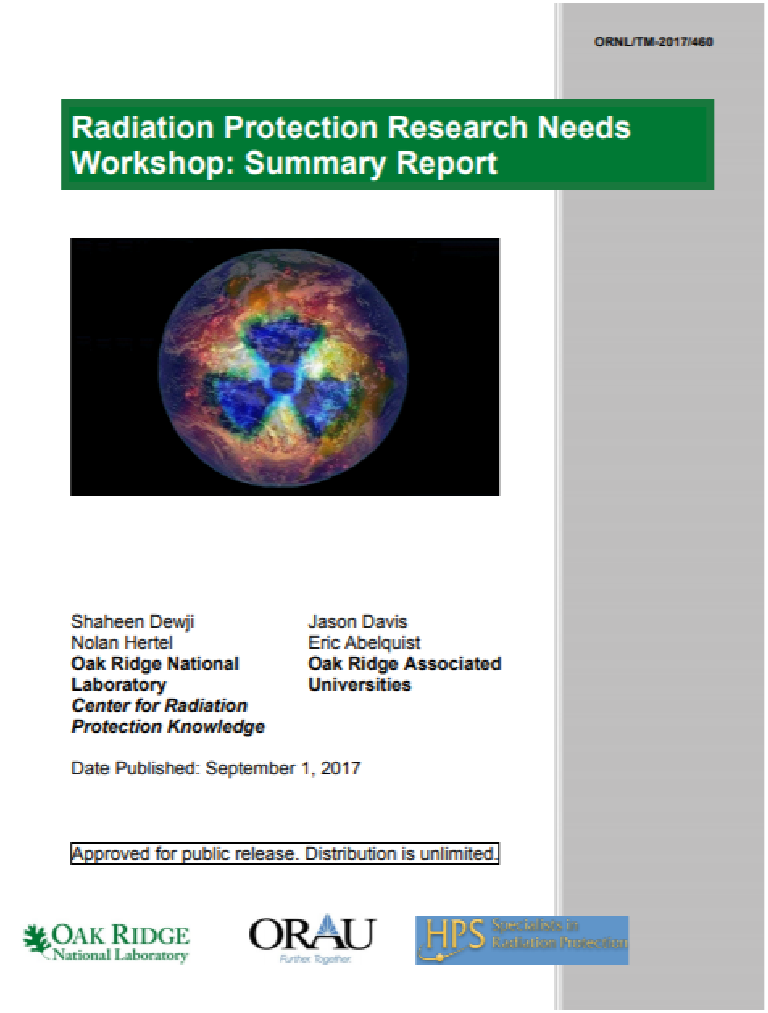
- *Fuel Fabrication and Enrichment*
  - *Criticality Safety*
  - *Criticality Accident Alarm Systems*
  - *Accident Dosimetry*
  - *Internal Dosimetry*
  - *Analytical Measurement Methods Developmen*
    - *DA*
    - *NDA*
  - *Nuclear Safety*
  - *Handling and Management of HEU (security, safeguards, 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”

- *Drafted Internal Document, on HP Knowledge Management, similar in effect, to the National Academies Report, “Assuring a Future U.S.-Based Nuclear and Radiochemistry Expertise,” (2012)*

- *Davis and Dewji et. al. organized a workshop, titled “Radiation Protection Research Needs”, June 5-6, 2017*
  – *Publication: “Synopsis of the Oak Ridge Radiation Protection Research Needs Workshop,”* ***Health Phys. 116(1):69–80; 2019***



ORNL/TM-2017/460

Radiation Protection Research Needs Workshop: Summary Report

Shaheen Dewji
Nolan Hertel
Oak Ridge National Laboratory
Center for Radiation Protection Knowledge

Jason Davis
Eric Abelquist
Oak Ridge Associated Universities

Date Published: September 1, 2017

Approved for public release. Distribution is unlimited.

OAK RIDGE National Laboratory
ORAU
HPS Specialists in Radiation Protection

Available at: https://info.ornl.gov/sites/publications/Files/Pub102365.pdf

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

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

Ref.: Dewji, S. "Radiation Protection Research Needs Workshop," *Prepared for:* International Dose Effect Alliance Workshop (IDEA), December 2017

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

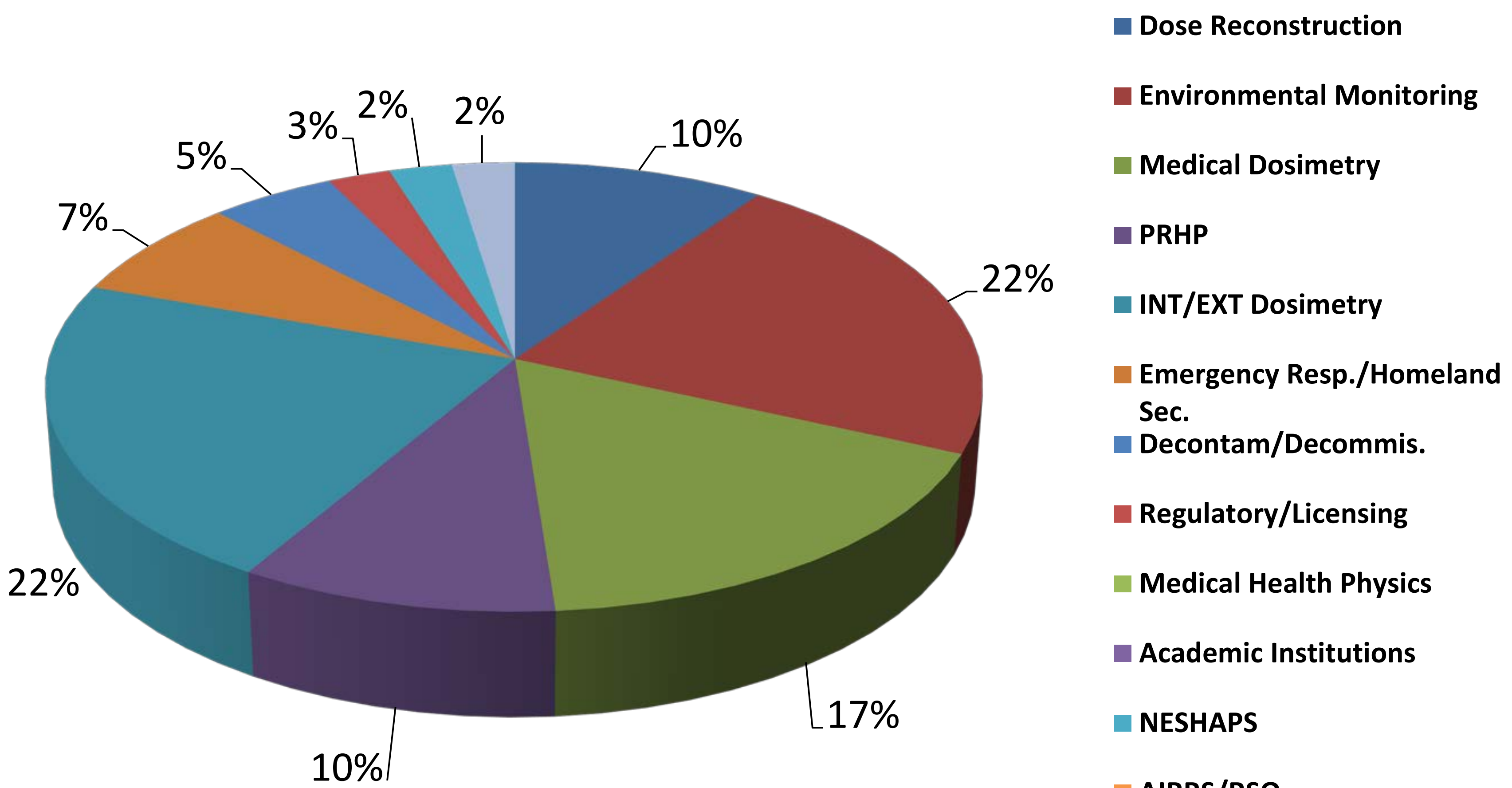
Space Radiation	National Defense	Emergency Response	Environmental Modeling
Optimization of shielding thickness Secondary radiation produced in shielding Cross sections for heavy, energetic particle interactions Comparative dose response studies Individual, genetic-based risk profiles Central nervous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

Ref.: Dewji, S. "Radiation Protection Research Needs Workshop," *Prepared for:* International Dose Effect Alliance Workshop (IDEA), December 2017

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

Experimental and Applied
vs.
Modelling and Computational

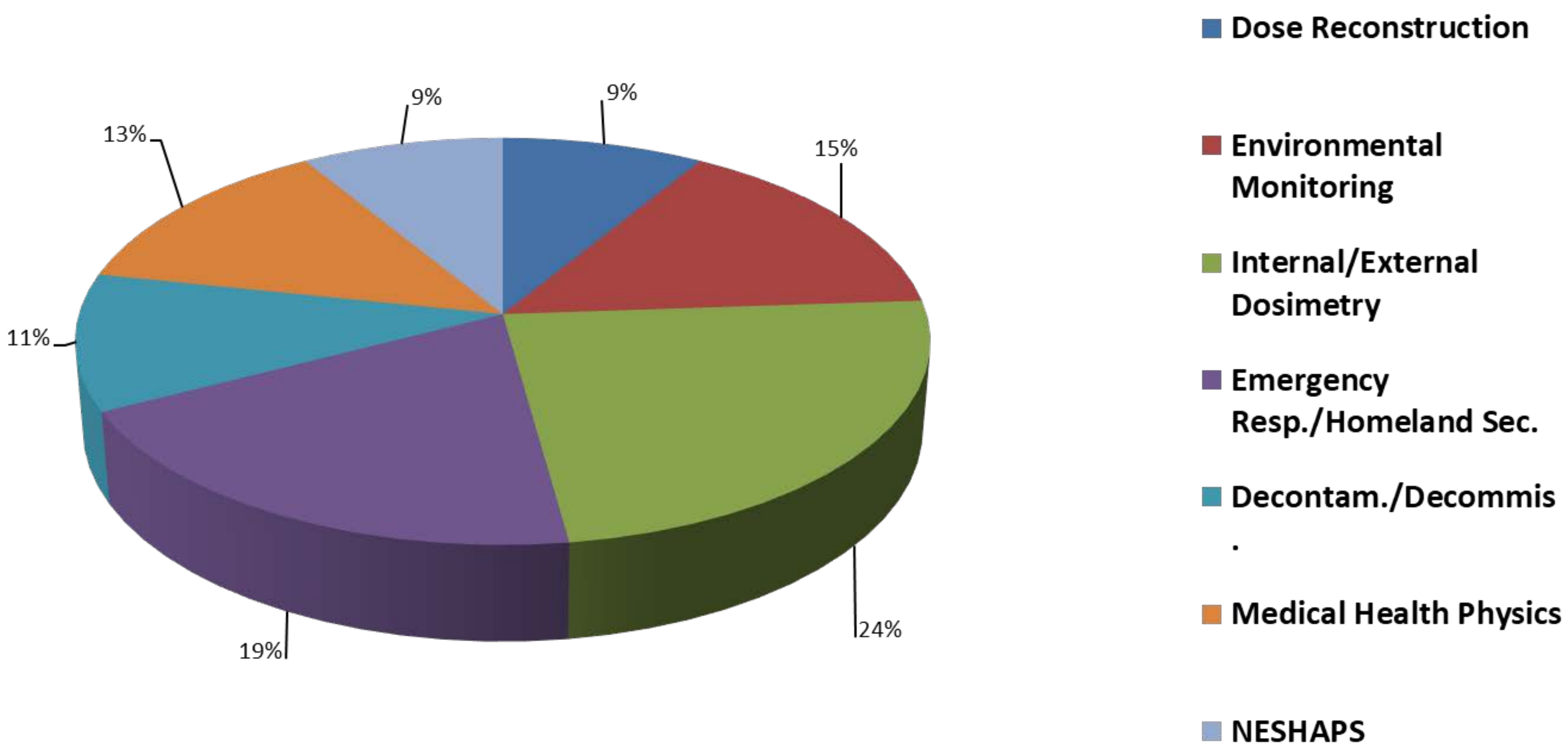
HPS Annual Meeting Papers Infrastructure, 2015



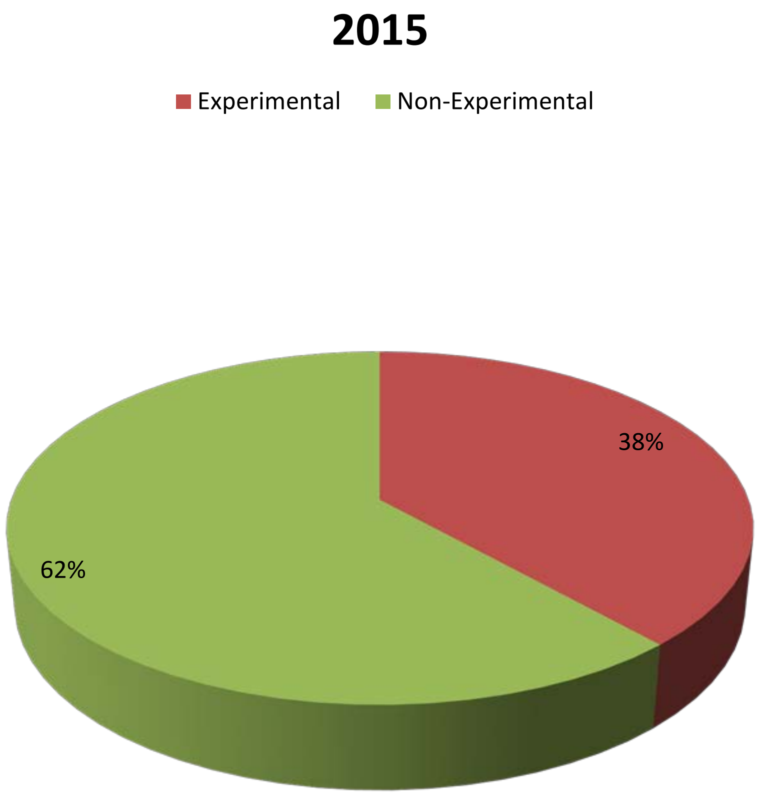
HPS 2015 Annual Meeting Program. **INFRASTRUCTURE AND EXPERIMENTATION:** Environmental Monitoring, Internal and External Dosimetry, and Medical Dosimetry

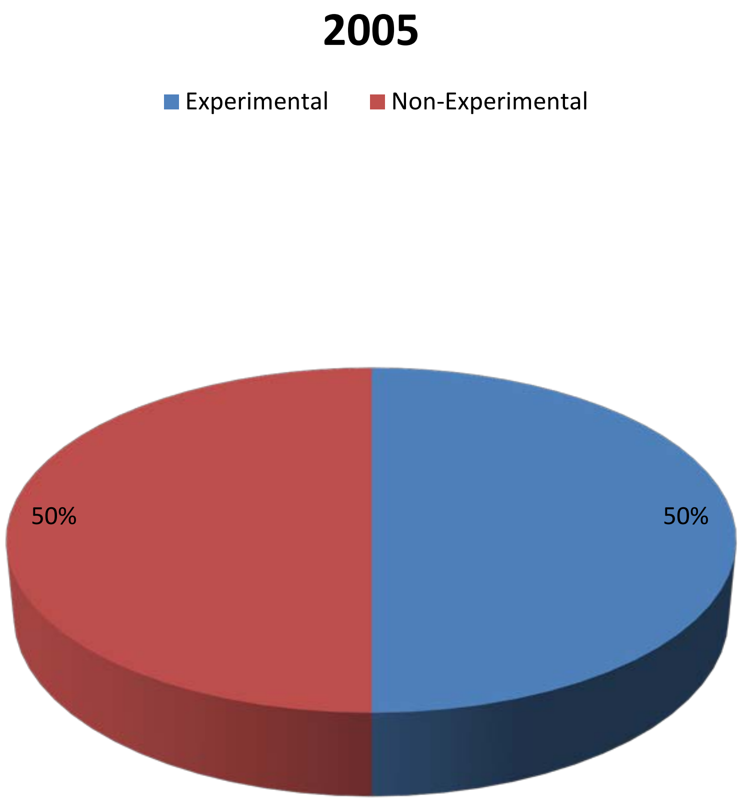
(Reference: Joseph Dirsa, ORNL Summer Intern)

HPS Annual Meeting Papers Infrastructure, 2005



HPS Annual Meeting Papers
Experimental Work (2015 vs. 2005)

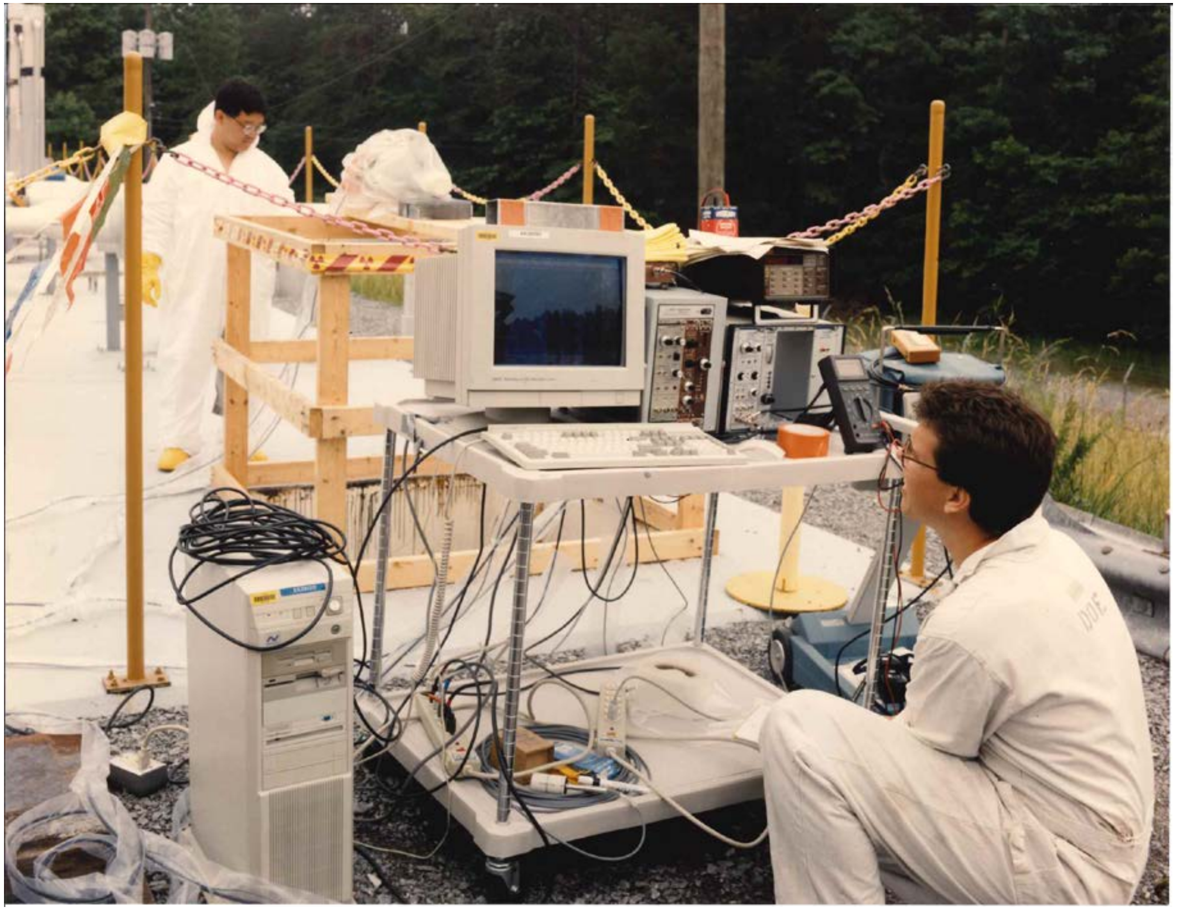




Examining the 2005 and 2015 HPS conferences, the amount of experimental/hands on work has seen a 12% decrease since 2005 (Reference: Joseph Dirsa, ORNL Summer Intern)

Turning Point #2: Technology Development – In-Situ Gamma-Ray Spectrometry

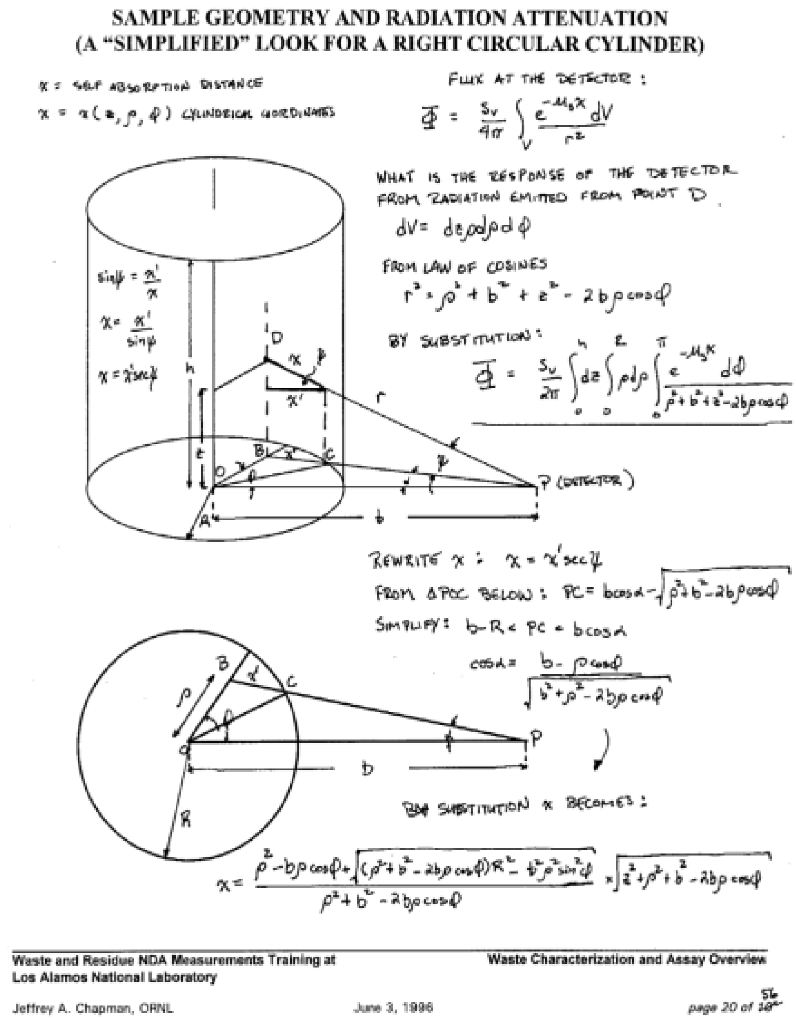
- *In-situ Gamma-Ray Spectrometry, Melton Valley Storage Tanks, 1992*



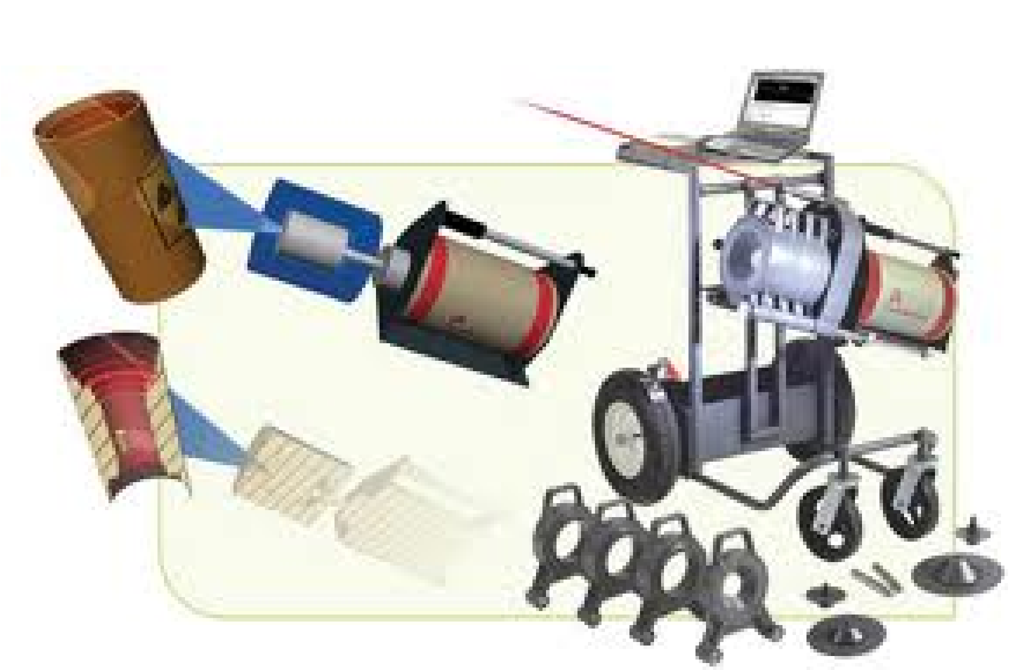
Turning Point #2: Technology Development – In-Situ Gamma-Ray Spectrometry

- 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



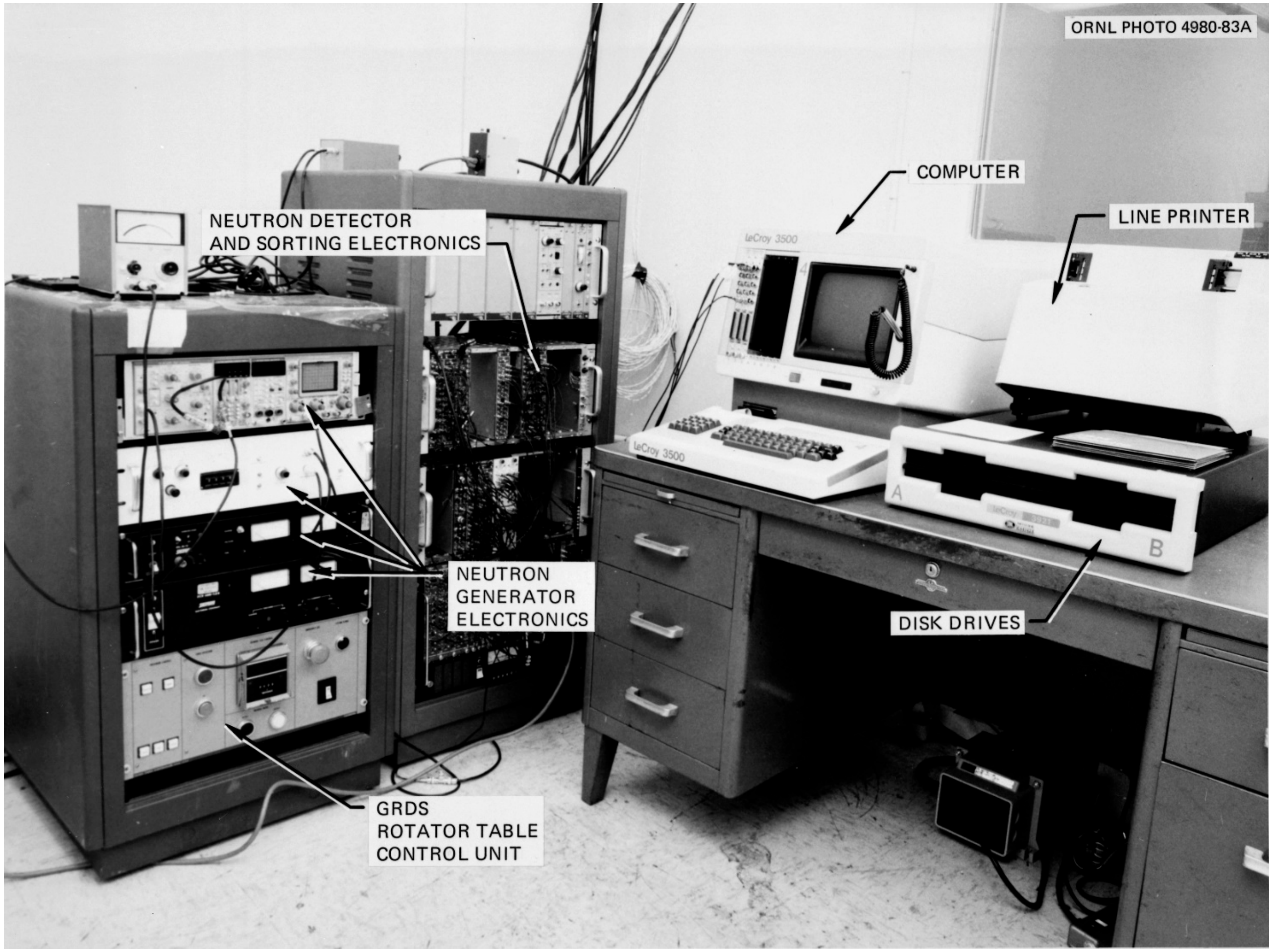
Canberra ISOCS (~1995)

Ortec ISO-CART (~2003)

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*



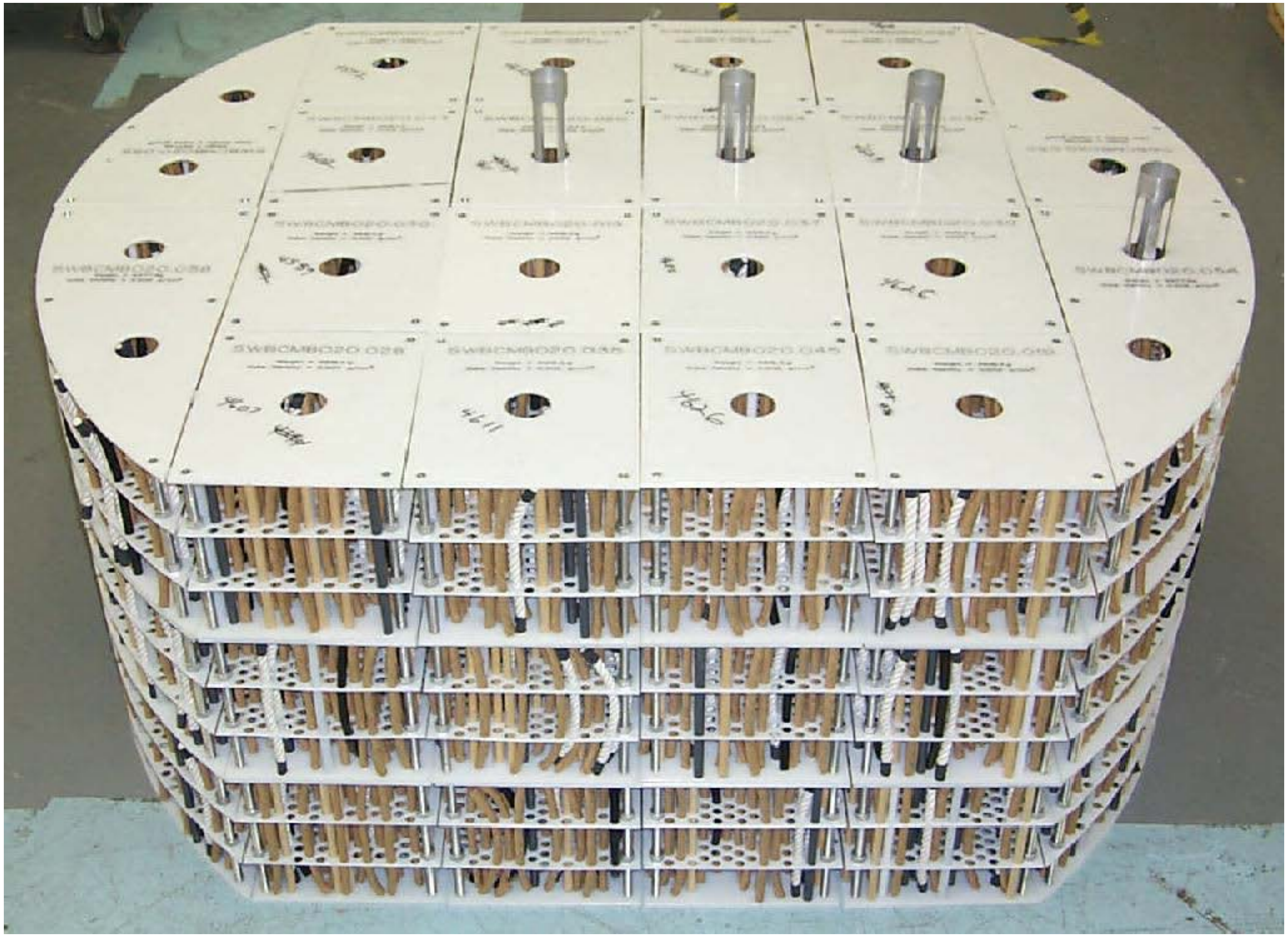
Turning Point #2: Technology Development- Active Neutron Interrogation (1984-1999)

Turning Point #2: Technology Development – Segmented Gamma-Ray Spectrometry (SGS), and Tomographic Spectrometry Scanning (TGS)

ORNL 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



Turning Point #2: Technology Development - Computational Modelling Supplements Calibration, Test and Evaluation of NDA Systems for WIPP TRU Waste

DOE/CBFO-01-1006
NDA Box PDP Plan

Revision 5
February 2015

Table 1. NDA PDP activity ranges and associated scoring acceptance criteria.

		Maximum Measured Precision[b]		Bias Range[c] ($\%R_L$ and $\%R_U$)	
Activity range	Range of sample activity in α-curies[a]	Non-interfering matrix (%RSD)	Interfering matrix (%RSD)	Non-interfering matrix (%R)	Interfering matrix (%R)
Low	> 0 to 0.02	14	16	Lower: 70 Upper: 130	Lower: 40 Upper: 160
Mid-Low	> 0.02 to 0.2	10.5	12	Lower: 70 Upper: 130	Lower: 40 Upper: 160
Mid-High	> 0.2 to 2.0	7	12	Lower: 70 Upper: 130	Lower: 40 Upper: 160
High	> 2.0	3.5	6	Lower: 70 Upper: 130	Lower: 40 Upper: 160

%R = percent recovery
%RSD = percent relative standard deviation

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.

Turning Point #2: Technology Development – Calibration, Test, and Evaluation of Uncertainty (Implementation of GUM)

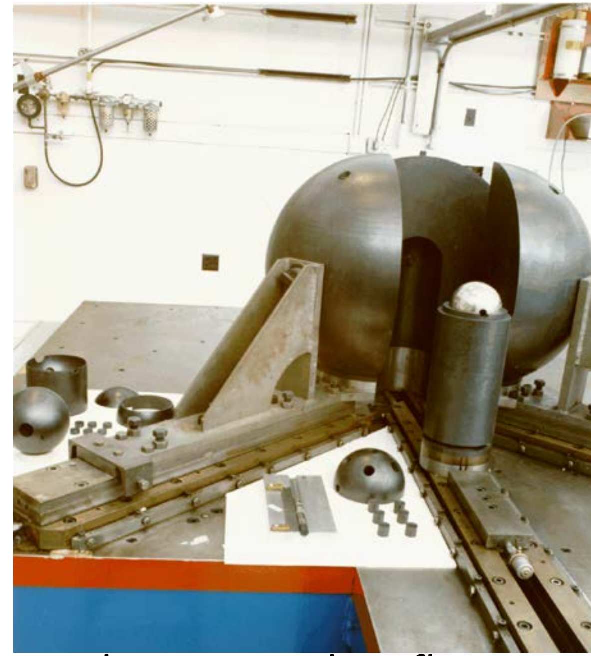
How do the characteristics of the standards effect the neutron based measurements?

- Mass – Used as standard
- Enrichment/Isotopics – Used for calculation of ^{235}U or ^{240}Pu$_{eff}$
- 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 (a,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

93.2% HEU metal foils



α-phase Pu, poly refl.

8 HEU shells (93.2%)

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*