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Challenges in Nuclear Nonproliferation: The Role of Nuclear Science and Scientists (alternate title: John Huizenga and Nuclear Nonproliferation)

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21 April 2006

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Outline

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- The battlefield
- Nonproliferation and JRH's science
- Nonproliferation and JRH's students
- The future

ACKNOWLEDGMENTS: Arden (Hoover) Dougan, Walt Hensley, Mary Anne Yates, Jim Sprinkle; if I've forgotten anyone, my apologies!

Terminology

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- “Nonproliferation”: The ensemble of activities to anticipate, deter, detect, and defeat the acquisition and use of nuclear weapons by adversaries, whether national, subnational, or supranational.
  - Nuclear counterterrorism is an important part of this set of activities; not the entire spectrum, but will be featured prominently here.
- “SNM”: Special nuclear materials, isotopes of plutonium and uranium useful in producing a fission weapon
- “HEU”: Highly enriched uranium, =20% ^{235}U [International Atomic Energy Agency (IAEA) definition]

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Classical Model of Nuclear Proliferation: The Ambitious Nation-State

For a nation-state:

- One bomb probably is not enough, so capacity to make multiple bombs (infrastructure) is likely
- Delivery systems important because target is presumed to be defended
- Valid nonmilitary reasons to produce and use SNM
    - Can provide “cover” for military production
- Nuclear material <u>production</u> is the rate-determining step

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If I wanted to execute a terrorist nuclear attack, I would…

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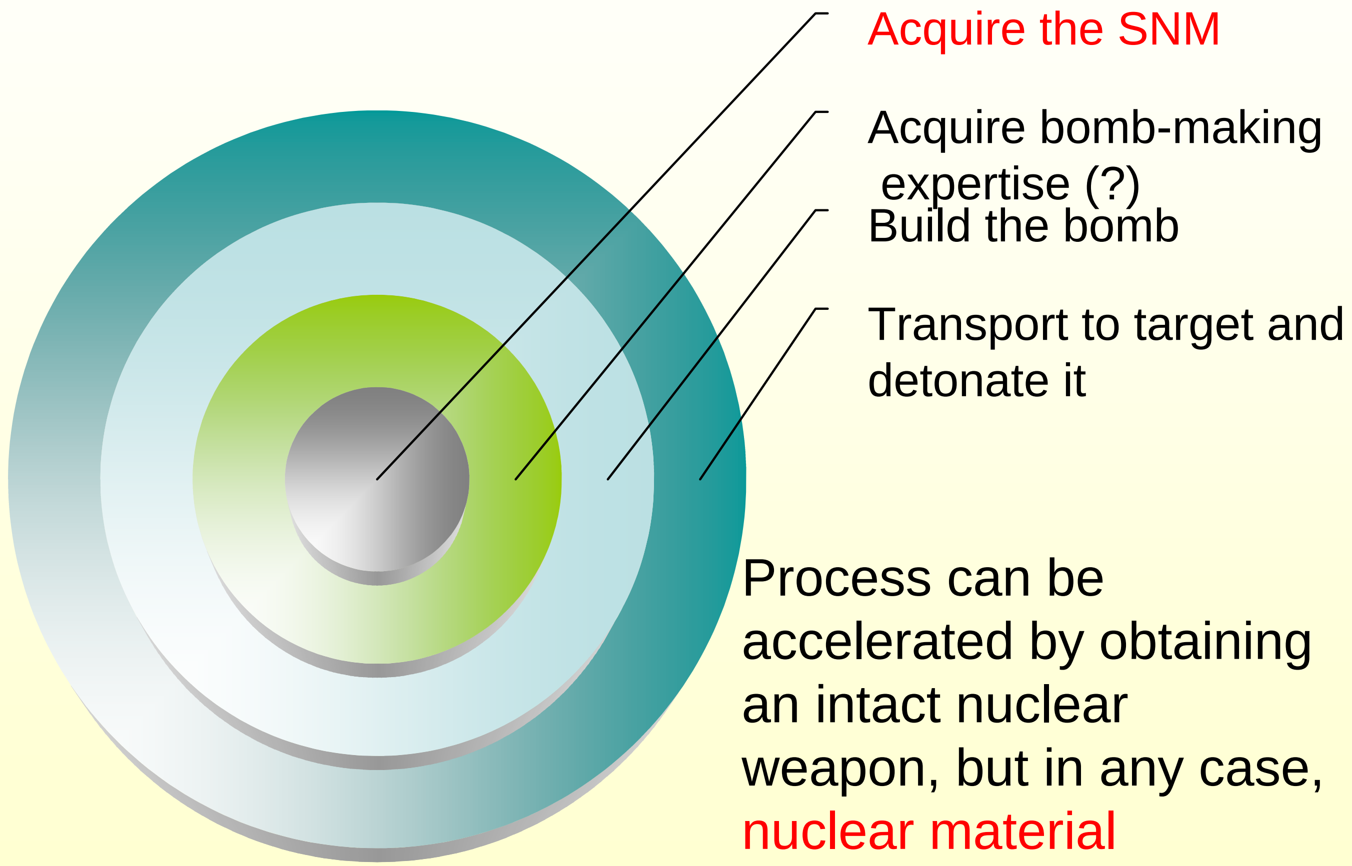
A key point: A terrorist group may need only <u>one</u> nuclear explosive to reach its goals, and that one does not necessarily have to work optimally.

This is different from the needs of a nation aspiring to nuclear-power status.



Process can be accelerated by obtaining an intact nuclear weapon, but in any case, <u>nuclear material acquisition</u> is the rate-determining step

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The bottom line: “It’s the SNM, stupid!”

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- Safeguards to detect diversion/misuse of otherwise legitimate nuclear materials
- Second line of defense (Megaports) to detect SNM in transit
- Homeland security (incl. PSI, CSI) to intercept inbound threats
- Emergency response (NEST) to deal with an intercepted device (not discussed here)
- Attribution and forensics to identify perpetrators and enablers of an attack so that they can be dealt with

Radiation detection and nuclear science are essential to all of these program components

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Spontaneous Fission of Selected Nuclides

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Nuclide	Specific Intensity [n/(g-s)]
^{235}U	0.0003
^{238}U	0.0136
^{238}Pu	2590.
^{239}Pu	0.022
^{240}Pu	1020.
^{241}Pu	0.05
^{242}Pu	1720.
^{237}Np	0.0001

Implication: U does not emit many neutrons, and the low percentage of ^{240}Pu in reactor-produced material is dominant

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Major Gamma-Ray Signatures (NB! Much relevant work done at NSRL)

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$$^{239}Pu \xrightarrow{24,000\ y} {}^{235}U^{*} + \alpha$$

Relatively complex decay scheme; major gamma rays:

129.28-keV Intensity 140,000 γ /(g-s)

413.69-keV Intensity 34,000 γ /(g-s)

$$^{235}U \xrightarrow{710,000,000\ y} {}^{231}Th^{*} + \alpha$$

Much simpler decay scheme; major gamma ray:

185.72-keV Intensity 43,000 γ /(g-s)

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Passive Neutron Multiplicity Counting: A Key Technique in Nuclear Safeguards

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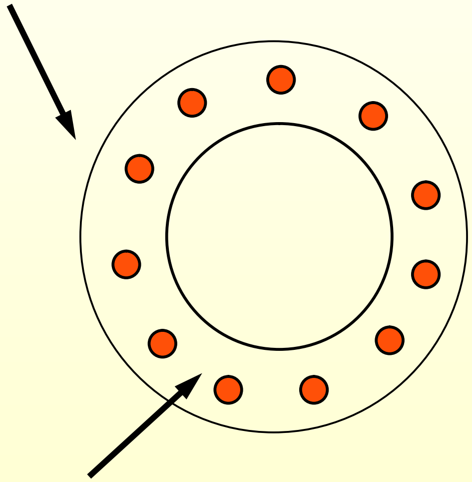
30-gallon drum counter

Thermalize neutrons in polyethylene



Capture in ^{3}He tubes

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Neutron Multiplicity

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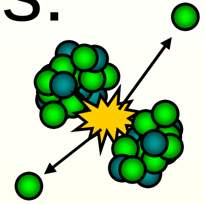
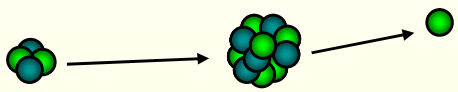
3 physical processes produce neutrons:

- Spontaneous fission (**F**)



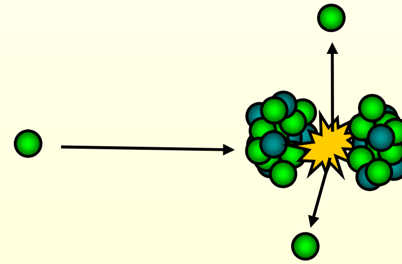
F

- (α,n) reactions



α

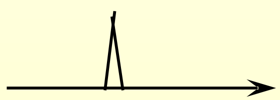
- Multiplication (**M**)



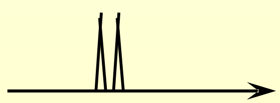
M

Need 3 rate measurements:

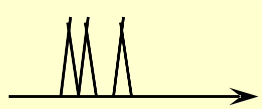
- "**S**ingles"



- "**D**oubles"



- "**T**riples"



For 3 equations to solve for 3 unknowns

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Using Neutron Multiplicity in Safeguards

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Key application: verifying inventories of plutonium in nuclear facilities.

- Goal: know the quantity F (total number of spontaneous fissions per second)
- If isotopics are known (derivable from γ spectrometry), conversion to total plutonium mass is straightforward
- Deduced mass can be checked against declarations to detect cheating or diversion

Why This Is So Important: the "Alcatraz Problem"

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- According to the IAEA, a "significant quantity" of plutonium is 8 kg
- But plutonium is produced in many-kg quantities by breeder reactors, etc.
- And diversion a few grams at a time is still a threat!
- Therefore, we want *every* measurement to be as precise as possible, and facilities must be *entirely* "escape-proof"

Unsolved problems still exist in this classic technique

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Point Model Equations

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$$S = F\varepsilon \nu_{s1} M (1+\alpha)$$

$$D = F\varepsilon^2 g M^2 / 2 \cdot \left[\nu_{s2} + \frac{M-1}{\nu_{i1}-1} \nu_{s1}(1+\alpha)\nu_{s2} \right]$$

$$T = F\varepsilon^3 g^2 M^3 / 6 \cdot \left[\nu_{s3} + \frac{M-1}{\nu_{i1}-1}\left(3\nu_{s2}\nu_{i2} + \nu_{s1}(1+\alpha)\nu_{i3}\right) + 3\left\{\frac{M-1}{\nu_{i1}-1}\right\}^2 \nu_{s1}(1+\alpha)\nu_{i2}^{\ 2} \right]$$

Where ε = detector absolute efficiency (determined empirically and/or by modeling)

g = coincidence gate correction (determined empirically)

ν_i = neutron multiplicities for induced and spontaneous fission—and here is where JRH comes in…

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The Key Assumption: Nuclear Physics Is Reducible to Constants Known *a priori*

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- In reality, $\nu=\nu(E_n)$ and the neutron energy spectrum are not known—or knowable—without detailed knowledge of both neutron emitters and reflector/moderators.
- Values for the ν_i therefore either must be
  - *Derived* from systematic knowledge of the behavior of neutron multiplicity as a function of neutron energy, combined with knowledge of relevant fission-neutron energy distributions; or
  - *Approximated* via Monte Carlo modeling (e.g., for detector effects).

Many of the key papers providing nuclear data to enable these calculations were co-authored by John Huizenga in the 1950s and 1960s.

Many challenges remain; more on this later

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Nuclear Event Attribution and John Huizenga's Science

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THE CHALLENGE: Identify the perpetrator of a successful nuclear attack.

- Unlike a conventional explosion (cf. Oklahoma City), a nuclear detonation destroys almost all evidence potentially useful in conventional criminal forensics.
- Analysis to deduce the perpetrator therefore must rely on
  - Knowledge of the capabilities of enemies (intelligence function, not covered here);
  - *Deducing the design and properties of the nuclear explosive* and comparing with the capabilities ("Rule out A, rule out B…").
  - Examples:
    - Uranium or plutonium? If plutonium, isotopic composition?
    - How sophisticated was the design?

A current, timely, and fascinating R&D topic that we cannot say much about, but…

An "Easy" Attribution Problem: HEU or Plutonium?

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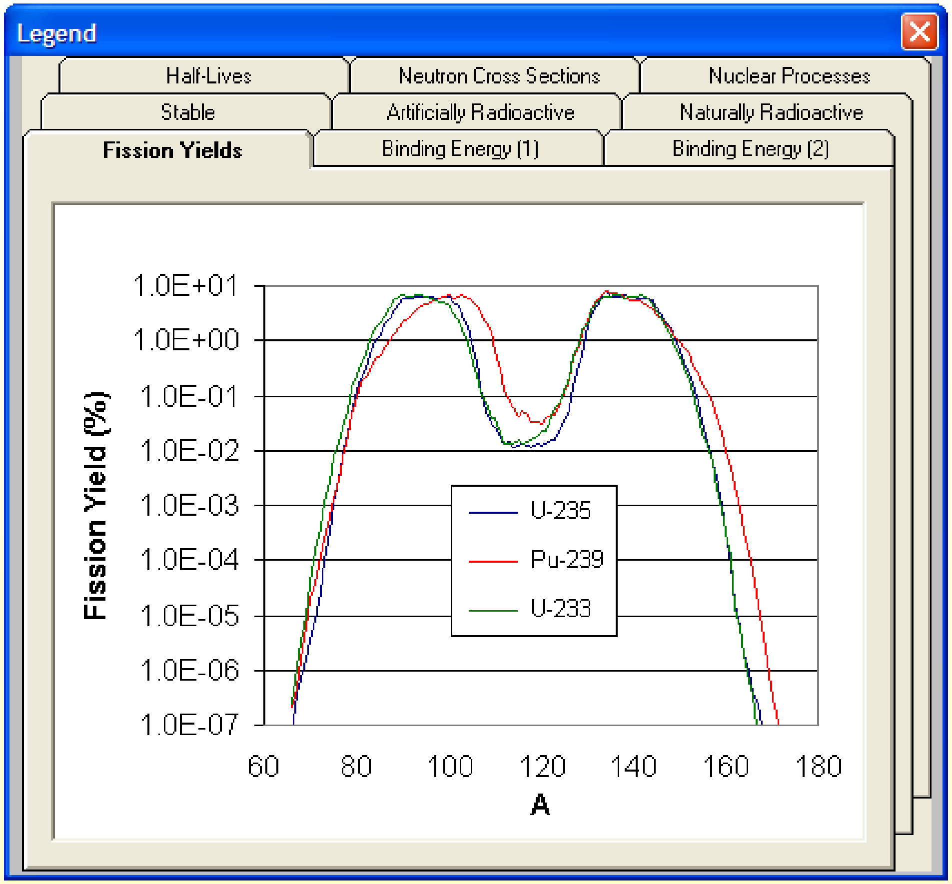
- Concept: collect debris from the explosion, do radiochemistry to determine abundances of key fission products
- Distribution of light fragments varies between fissioning ^{235}U and ^{239}Pu, particularly on "wings" of the distribution
- Complications from volatiles, fractionation, etc.; key nuclides may not be the most obvious ones
- *Need not just good distribution data, codified in databases, but good understanding (JRH papers from 1950s, 1960s)*
- Most science "worked out" by now, but always want to do radchem faster, etc.



Fission-product abundances generated by *Nuclide Navigator* (W. K. Hensley, PNNL; UR Ph.D. 1973!)

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A “Hard” (Current!) Attribution Problem: Americium ΔA for Attribution (M. Chadwick *et al.*)

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$$^{240}\mathrm{Am} \rightleftarrows \boxed{^{241}\mathrm{Am}} \rightleftarrows {}^{242}\mathrm{Am} \rightleftarrows {}^{243}\mathrm{Am} \rightleftarrows {}^{244}\mathrm{Am}$$

Production-depletion inventory chain for americium isotopes

- ^{241}Am is an impurity in plutonium. It provides an in-situ diagnostic, and after a detonation one can measure
  - ^{240}Am production (measures high-energy neutrons, n2n)
  - ^{242}Am $\Rightarrow$ ^{242}Cm (measures low-energy neutrons, n,γ)
- Then compare measured values to predictions for postulated threat devices (“Rule out A, rule out B”)
- Americium ENDF nuclear cross-section databases, and simulation codes to use these data, are being developed

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Previous Americium Cross-Section Data in Evaluated Libraries in Poor Shape: Upgrades Essential (Factor of ~2 Error)

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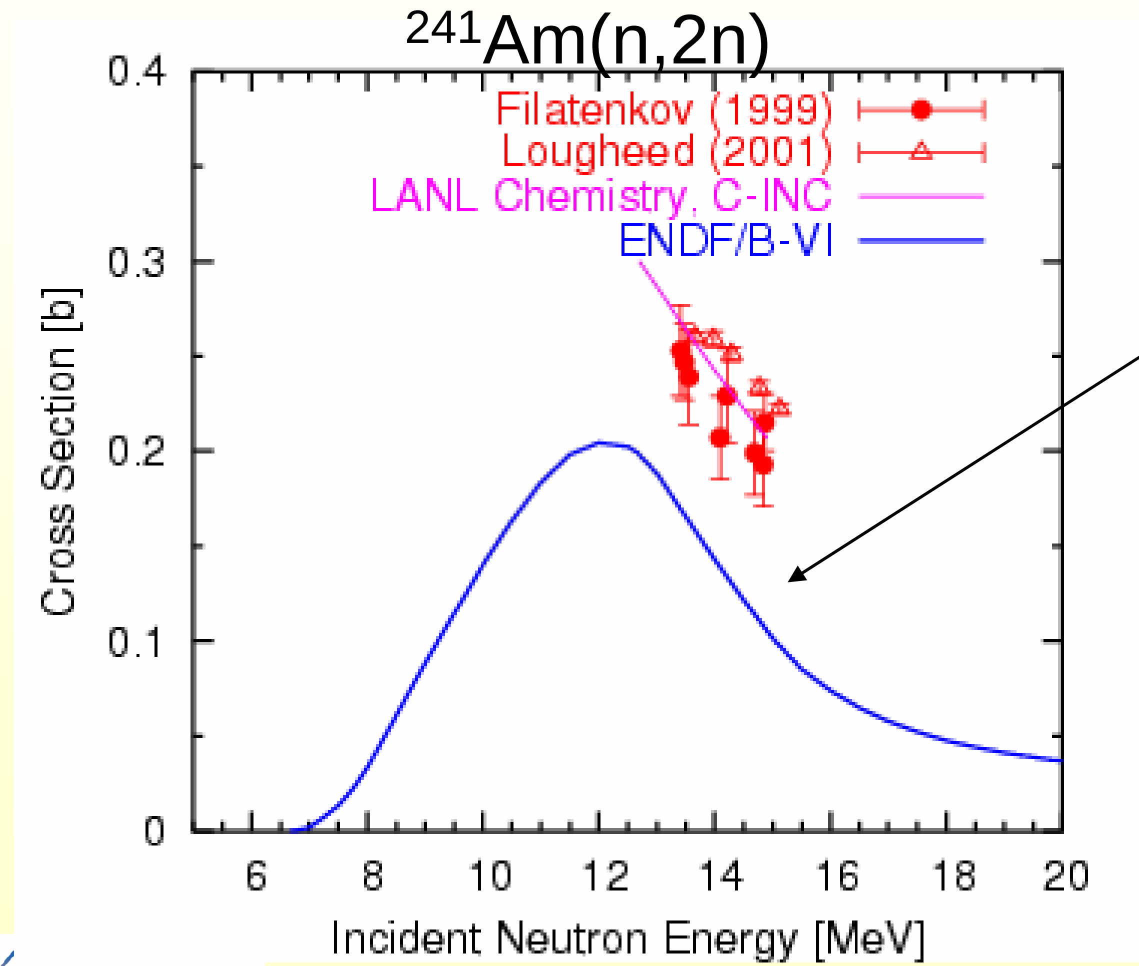

Previous evaluation done before measurements were made

Based on nuclear model calculations—but these are very difficult without experimental guidance when there is fission

Experimental work can help here

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Department of Energy's Second Line of Defense Program: Preventing Illicit Trafficking of Nuclear Materials across International Borders

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- Office of Second Line of Defense (SLD) works to prevent illicit trafficking in nuclear and radiological materials by securing international land borders, seaports, and airports that may be used as smuggling routes for materials needed for a nuclear device or a radiological dispersal device.
- Train and pedestrian portal monitors seen here detect contraband nuclear material, as seen in Astrakhan, Russia

A. Dougan

This and the next two slides courtesy of Arden (Hoover) Dougan, LLNL; Ph.D. 1982

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Russian Collaborations to Prevent Nuclear Proliferation

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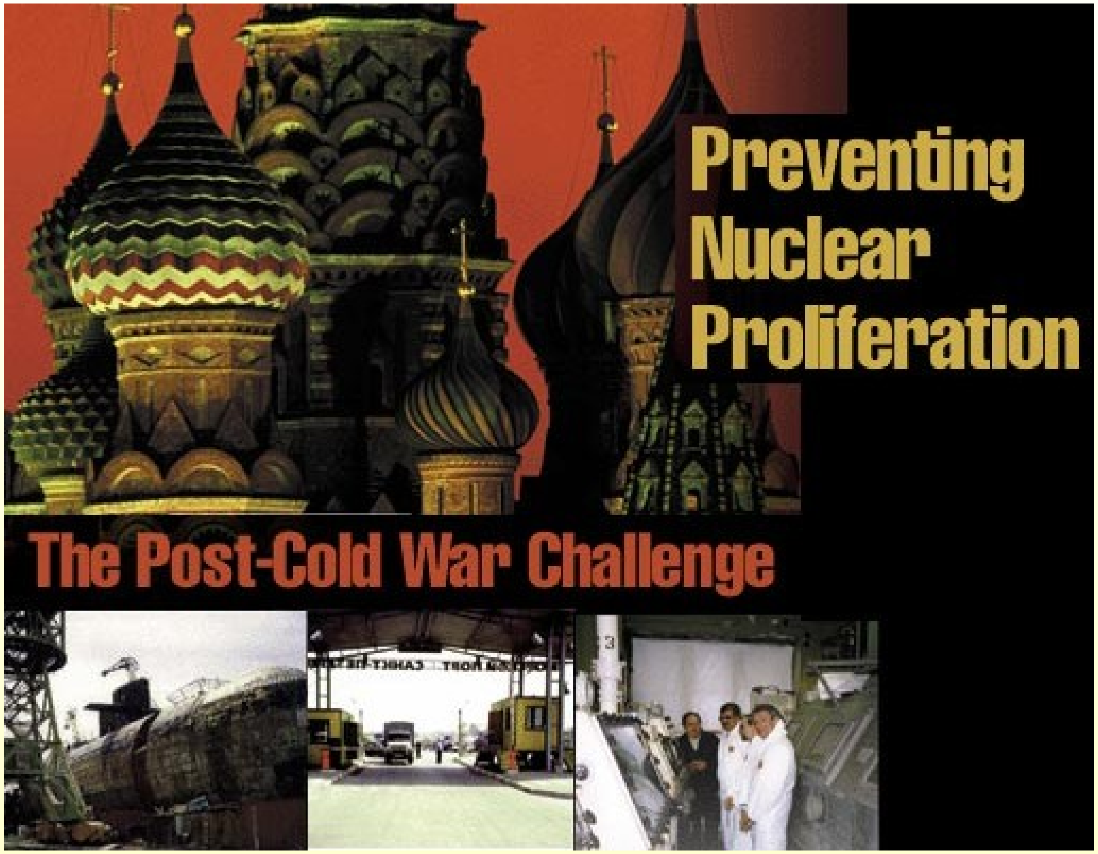

A. Dougan

- Current cooperative projects include development of technology for safe dismantlement and transparency, as well as counterterrorism
  - Development and testing of information barrier concepts, technologies, and procedures
  - Detecting high explosives and fissile material in cargo containers with “Associated Particle Imaging” technology
  - Development of a crane-mounted radiation detector to detect fissile material as contraband

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Nuclear Car Wash: Active Interrogation of Cargo Containers to Detect Contraband Nuclear Materials

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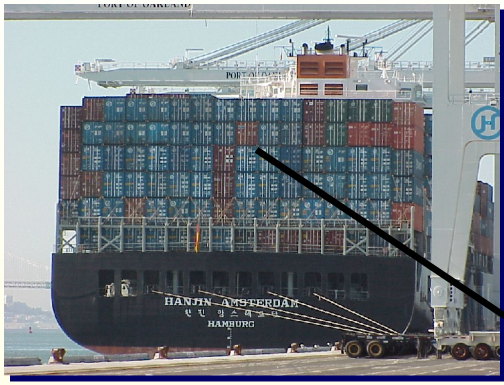

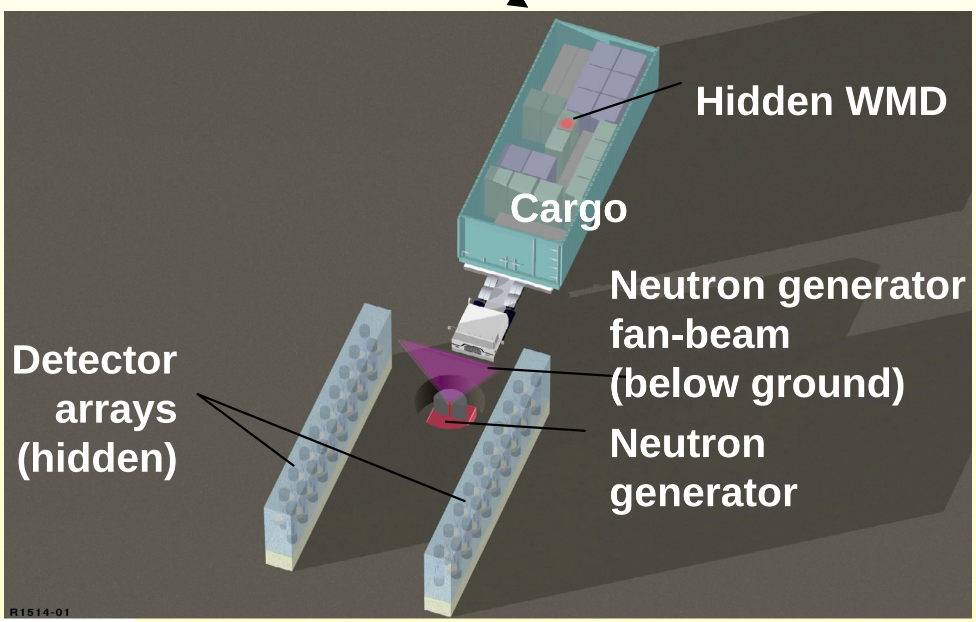

- A pulsed neutron beam interrogates the cargo
- NM is detected by observing fission product decays between pulses
  - Delayed neutrons
  - High-energy delayed γ-rays
- Chemical assay is obtained from neutron capture γ-rays during pulse

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D. Slaughter, A. Dougan, et al. IEEE Sensors Journal, vol. 5, no. 4, August 1, 2005, pp. 560-564

Super*SYNTH* (W. K. Hensley, PNNL; Ph.D. 1973)

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A Gamma-Ray Spectroscopy Interface to MCNP and MCNPX™

- The challenge: develop a simple way to represent/simulate source-detector response under real-world conditions.
  - Spectra of real-world threat objects differ from literature branching ratios owing to self-attenuation, shielding, etc.
  - Need to know real detector response for algorithm development, sensitivity studies
  - Full-blown Monte Carlo simulation is unnecessary for some problems
- Response: an easy-to-use software package for spectrum simulation that interfaces to more powerful Monte Carlo techniques
- Users: instrument developers, spectrum analysts (e.g., for understanding spectra of objects encountered in search and at portal monitors)

Super*SYNTH* Features

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- Multiple source geometries (Point, Shell, Sphere, and Disk geometries currently are supported)
- No limitations on source, absorber, or detector materials. All you need is a chemical formula and bulk density!
- No limitations on detector sizes
- Complicated source terms are easily created
  - Multiple isotopes with different quantities and ages
  - Quantities of daughter products are automatically calculated with the Bateman equations

Super*SYNTH* Features (cont)

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- Full photon transport by MCNP/MCNPX™ provides all of the detailed physics and spectral features, including
  - Full energy peaks
  - Escape peaks
  - Backscatter peaks
  - Fluorescence peaks
  - Compton continuum
  - Multiple Compton region
  - Buildup through thick absorbers

Other Nonproliferation Workers with JRH/NSRL Backgrounds

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- Mary Anne Yates (BS 1971): Deputy Director, Center for Homeland Security, Los Alamos; presently transitioning to Argonne
- Jim Sprinkle (MS 1977, Cline): Deputy Group Leader, Safeguards Science and Technology group, Los Alamos
- Merlyn Krick (NSRL post-doc late 1960s) and Phyllis Russo (NSRL post-doc late 1970s): recently retired from Safeguards Science and Technology, Los Alamos
- Mark Waterman (BS 1979): Offsite Source Recovery Program, Los Alamos

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The Future

"Mission" challenges remain much as they have been:

- Ensuring safe and secure storage and handling of nuclear materials
- Detecting diversion of nuclear materials for nefarious purposes (while promoting legitimate commerce and use)
- Dealing with Cold War legacy materials
- Detecting and defeating threats to use nuclear materials contrary to the national well-being
- Attribution and forensics in the event of a nuclear attack or nuclear smuggling

However, some of the technical problems are new.

"Hard-to-Measure" Materials: A Challenge in Nuclear Safeguards

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The point-model equations—

$$S = F\varepsilon \nu_{s1} M(1+\alpha)$$

$$D = F\varepsilon^2 g M^2 / 2 \cdot \left[\nu_{s2} + \frac{M-1}{\nu_{i1}-1} \nu_{s1}(1+\alpha)\nu_{s2} \right]$$

$$T = F\varepsilon^3 g^2 M^3 / 6 \cdot \left[\nu_{s3} + \frac{M-1}{\nu_{i1}-1}\left(3\nu_{s2}\nu_{i2} + \nu_{s1}(1+\alpha)\nu_{i3}\right) + 3\left\{\frac{M-1}{\nu_{i1}-1}\right\}^2 \nu_{s1}(1+\alpha)\nu_{i2}^{\ 2} \right]$$

—run into trouble if α is large (many (α,n) neutrons). Possible solution: reduce importance of g; possible by replacing thermal detectors (^{3}He tubes) with detectors for fast neutrons.

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Isotope Identification: A Hard Problem in SLD and Homeland Security

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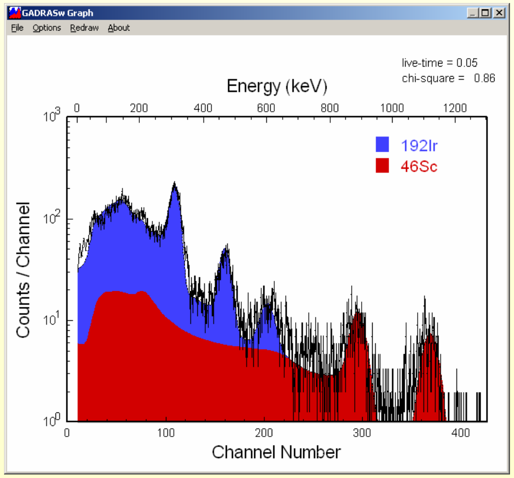
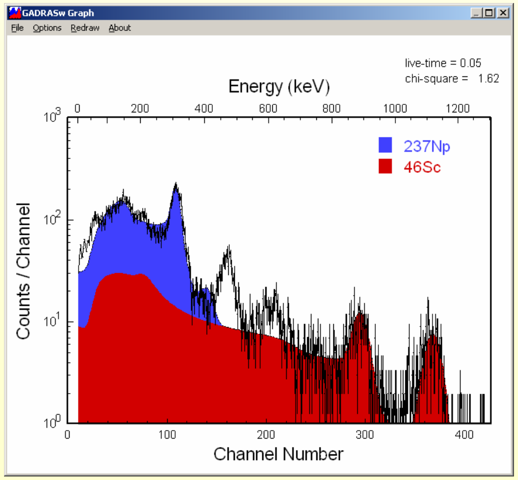
PROBLEM:

- Portal monitors do not (yet) have spectroscopic capability, so they cannot distinguish between threats and benign sources.
- Handheld isotope identifiers are used for anomaly resolution, but they have low resolution, are not robust, and are error prone.

POSSIBLE SOLUTIONS:

- Spectroscopic portal monitors (?)
- Improved isotope identifiers
  - Detector materials with better energy resolution
  - Make existing materials cheaper
  - Better algorithms





False positives not as bad as false negatives, but still…

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Problems in Active Interrogation

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Active interrogation (illuminating a suspect item with γs or neutrons, looking for γ or n from induced fission) is crucial for detecting shielded SNM, particularly HEU (because ^{235}U is not very radioactive), but many practical difficulties.

- Build a small, cheap, portable, intense (tunable/pulsable) source, and the world will beat a path to your door
- System optimization is difficult
  - Vital to minimize radiation dose to legitimate commerce and personnel
  - What is efficient for dealing with high-Z shielding may be inefficient for low-Z and vice versa
  - Is there exploitable physics we have not thought of? (resonances)
- Many unknowns regarding backgrounds (e.g., delayed neutrons from ^{17}N)

Problems in Attribution

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- Cross sections for neutron reactions on short-lived species are incompletely known (and can be important, e.g., ^{242}Am(n,2n))
- Existing radiochemistry is based on the old testing program and needs to be accelerated
- Much related work needed in blast effects, atmospheric effects, determining yield, etc.

In Conclusion

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John Huizenga has enriched and enabled the national program in nuclear nonproliferation through his *science*, his *students*, and his *intellectual legacy*.

There is still many a career to be made for the nuclear scientist in nonproliferation.

See you there!