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A Framework for the Solution of Inverse Transport Problems

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Inverse Radiation Transport

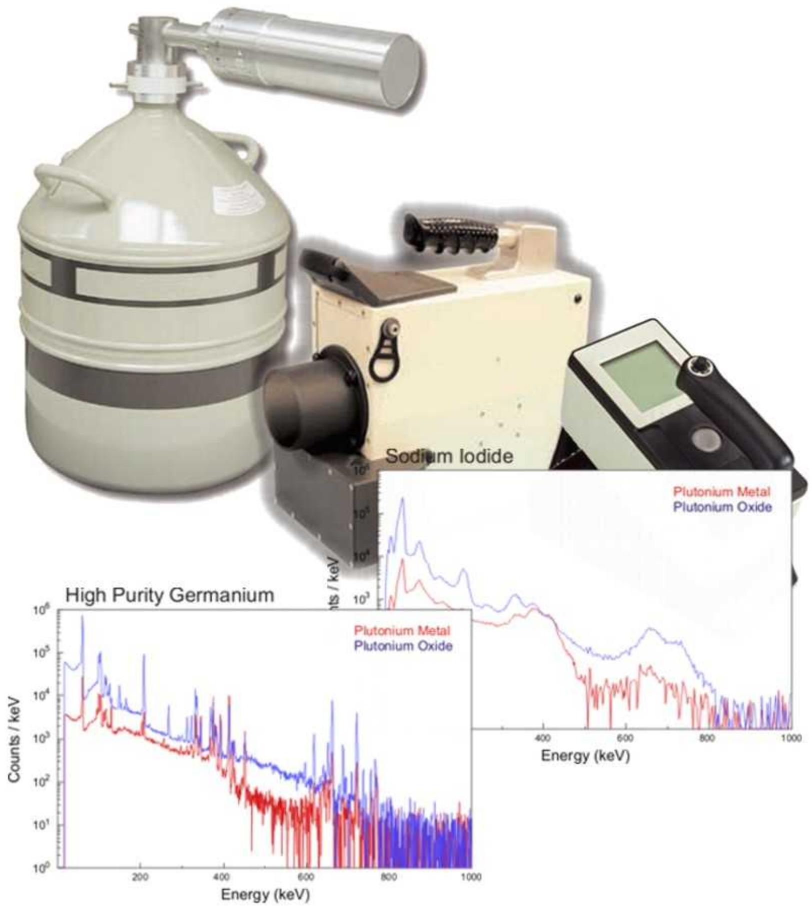
- Objective: infer properties of unknown radiation source from measured detector responses

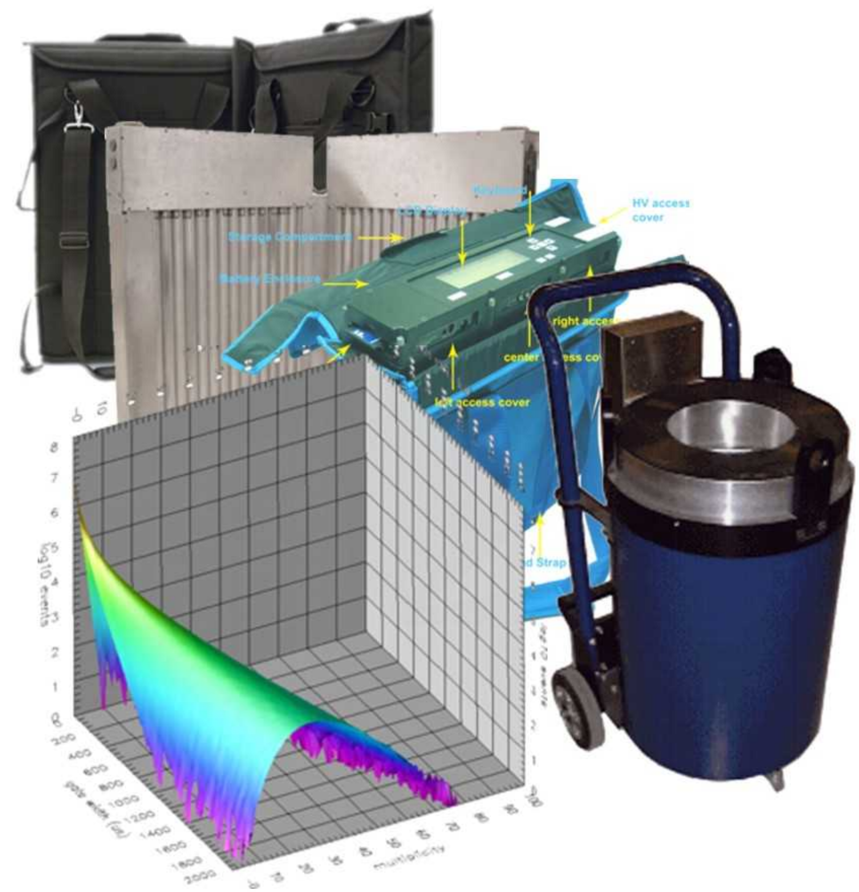
- Radiation source properties:
  - Isotopic composition
  - Fissile mass
  - Shielding
  - Geometric configuration

- Radiation measurements:
  - Gamma spectrometry
  - Neutron multiplicity counting

Radiation Detectors and Measurements

Gamma Spectrometers





Neutron Multiplicity Counters

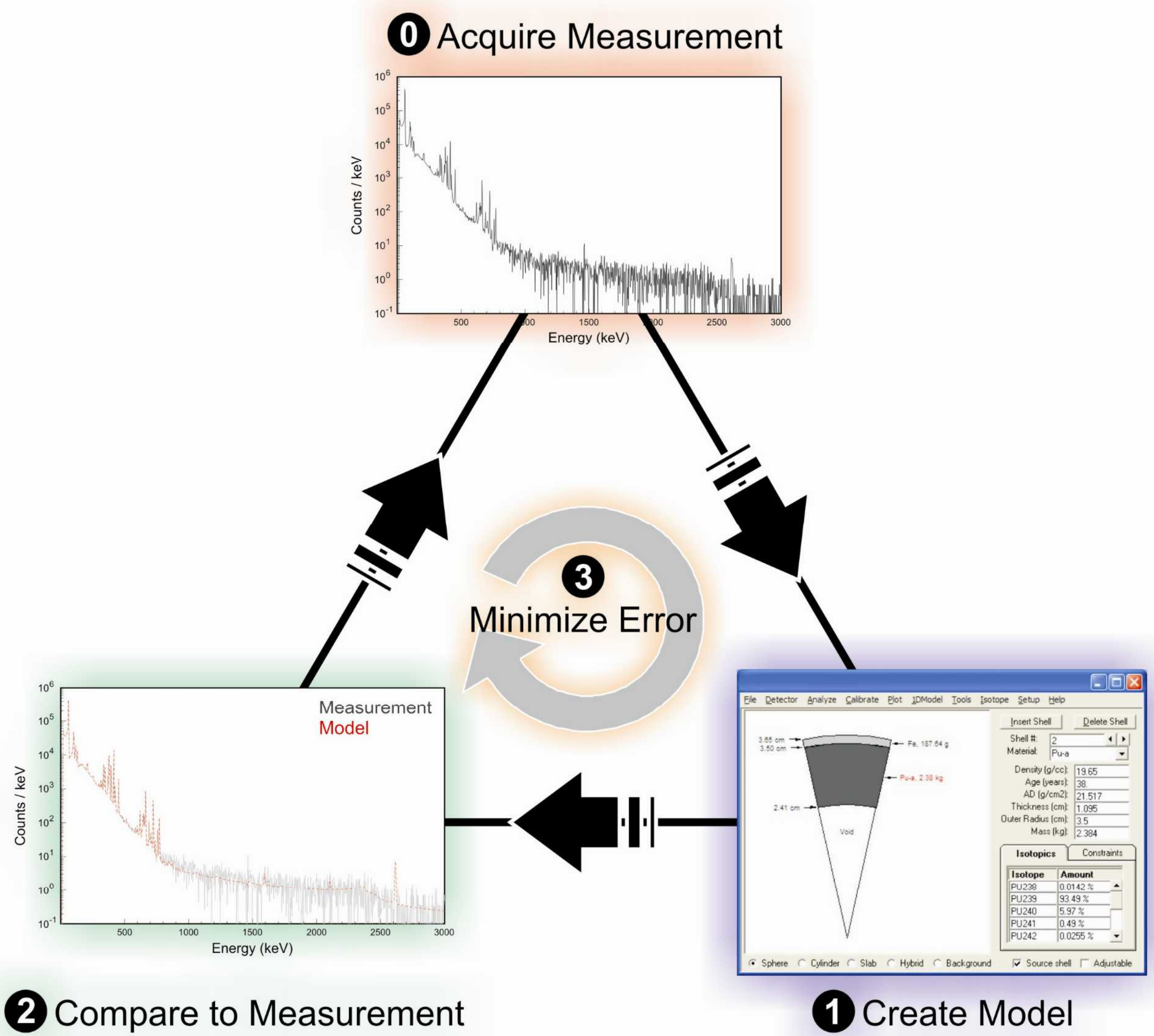
Technical Approach

- Use iterative optimization of forward transport models to identify source properties consistent with measured detector responses

- Solution steps:
  - Hypothesize model of source
  - Compute detector responses
  - Compare to measured responses
  - Iteratively refine model parameters to minimize error in calculated responses

- Components of framework:
  - Source term synthesis
  - Radiation transport solver
  - Detector response model
  - Nonlinear optimization procedure

Iterative Optimization Approach



Source Term Synthesis

- Account for radiation source terms that significantly contribute to detector responses

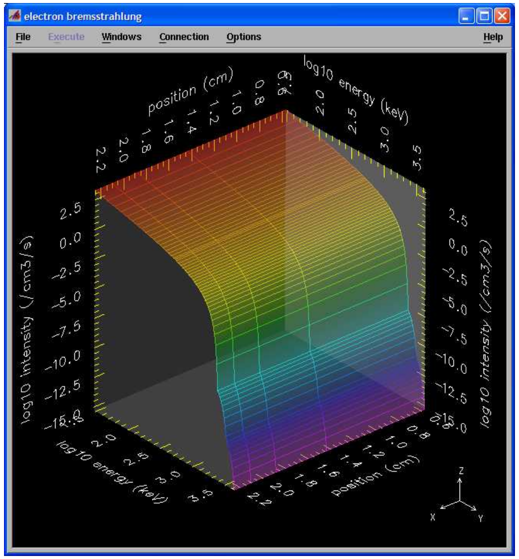
- Electrons from beta decay
  - Endpoint energies and yields from ENSDF
  - Fermi beta spectrum model

- Neutrons from
  - Spontaneous fission: Watt fission spectrum
  - (α,n) reactions: α-transport in homogeneous materials and across material interfaces
  - Implementation uses Los Alamos code SOURCES-4C

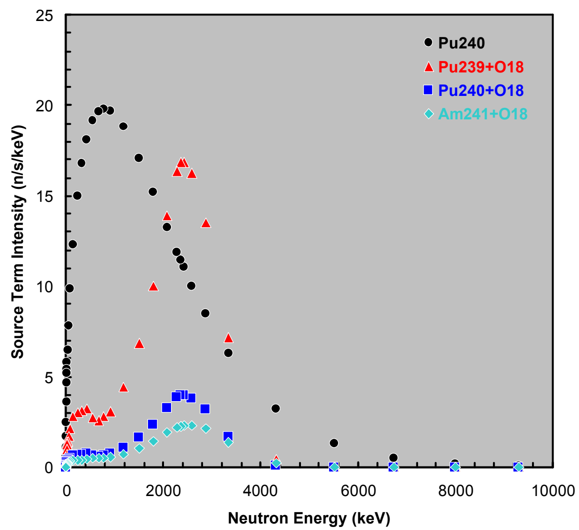
- Photons from
  - Nuclear decay: gamma energies and yields from ENSDF
  - Spontaneous & induced fission: Maienschein model of prompt & delayed fission gamma spectrum
  - (α,*) reactions: (α,*) reaction product levels from GNASH & ENSDF, population rates & branch ratios from experiment
  - (n,γ) reactions: cross-sections from ENDF-VI and ACTI libraries
  - Electron-bremsstrahlung: cross-sections from ITS

Radiation Source Terms

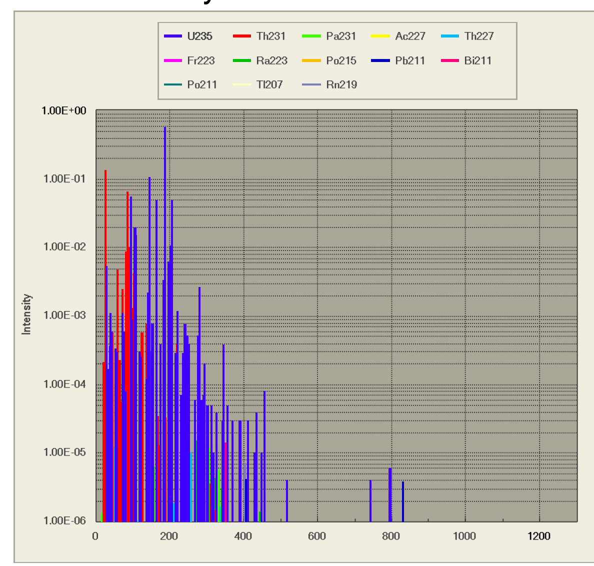
U(nat) Bremsstrahlung



PuO$_2$ Neutron Sources



U-235 Decay Gammas



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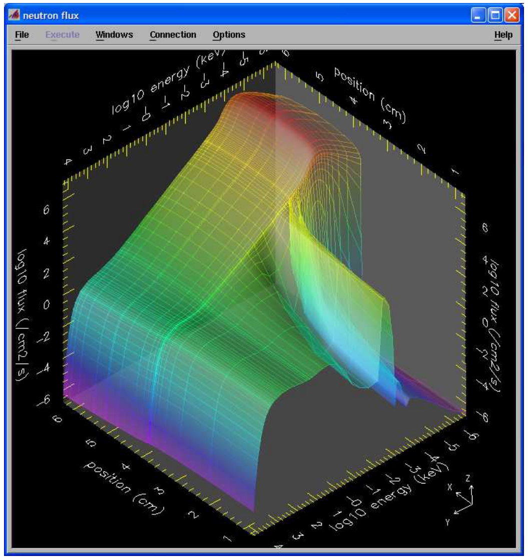
Radiation Transport

- Solve Boltzmann transport equation for particle flux and leakage current
- Implementation uses combination of S_N deterministic transport and photon ray-tracing

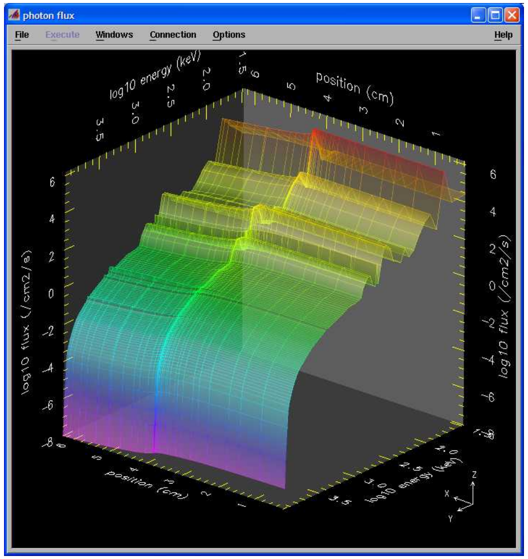
- Neutron solver: PARTISN
  - Neutron flux used to compute (n,γ) source terms
  - Neutron leakage used to compute detector neutron response
- Electron solver: ONELD
  - Electron flux used to compute electron-bremsstrahlung source terms
- Photon solver: ONELD
  - Photon flux used to compute fluorescence x-ray production
  - Photon leakage used to compute gamma spectrum continuum
- Photon ray-tracer
  - Computes uncollided discrete-energy photon leakage
  - Used to compute gamma spectrum photopeaks to arbitrary resolution

Radiation Transport Solution

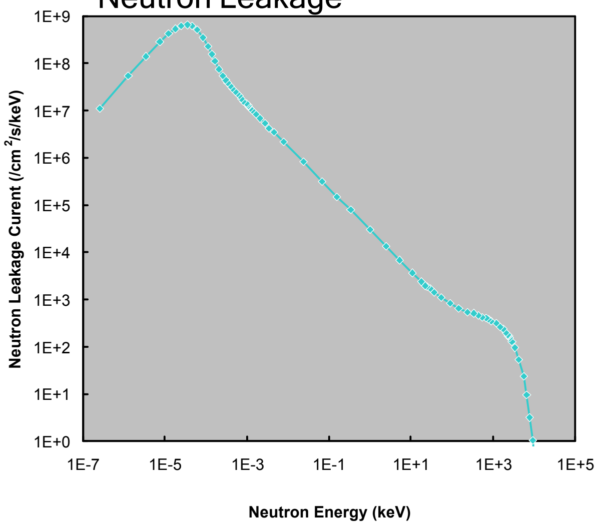
Neutron Flux



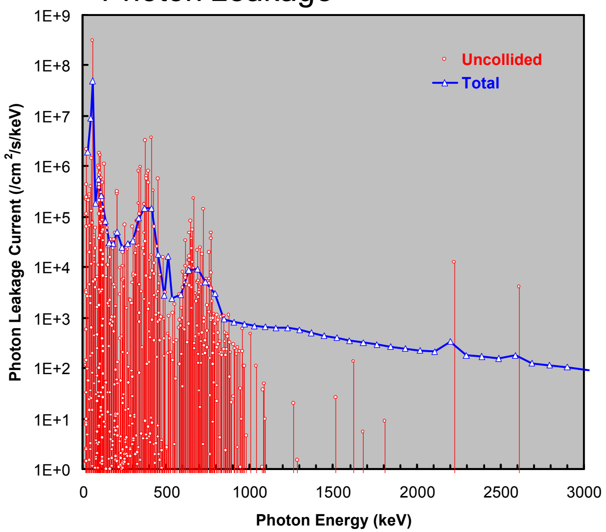
Photon Flux



Neutron Leakage



Photon Leakage



Detector Response Model

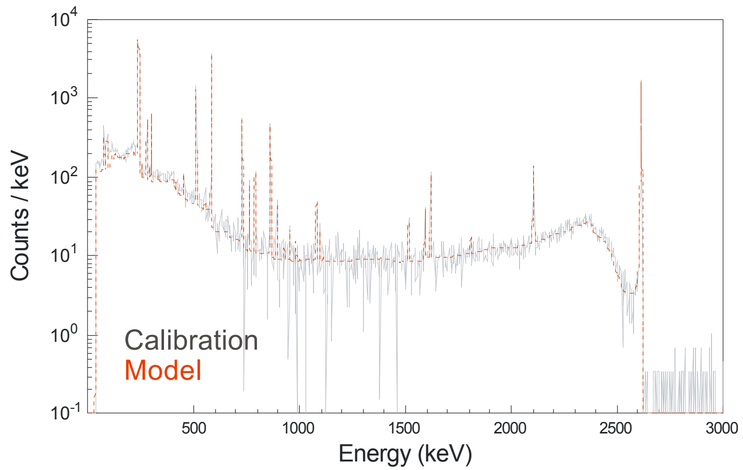
- Model detector characteristics that produce significant features in measured response

- Gamma spectrometers
  - Detector material: photoelectric, Compton scatter, and pair-production cross-sections
  - Neutron sensitivity: (n,γ) and (n,n') cross-sections and gamma yields
  - Detector size, shape, and orientation relative to source
  - Energy calibration and resolution
  - Shielding and collimation
  - Near- and far-field photon scatter

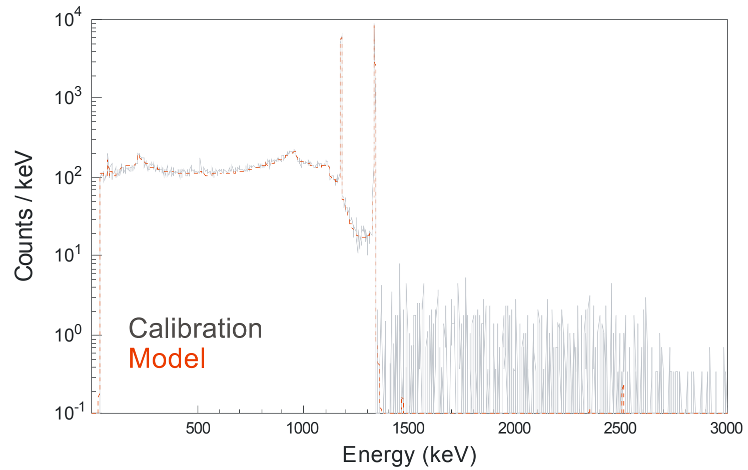
- Neutron multiplicity counters
  - Neutron efficiency vs. energy: detector material, moderation, reflection, and neutron absorption
  - Neutron slowing-down time in detector moderator

Gamma Detector Response Calibration

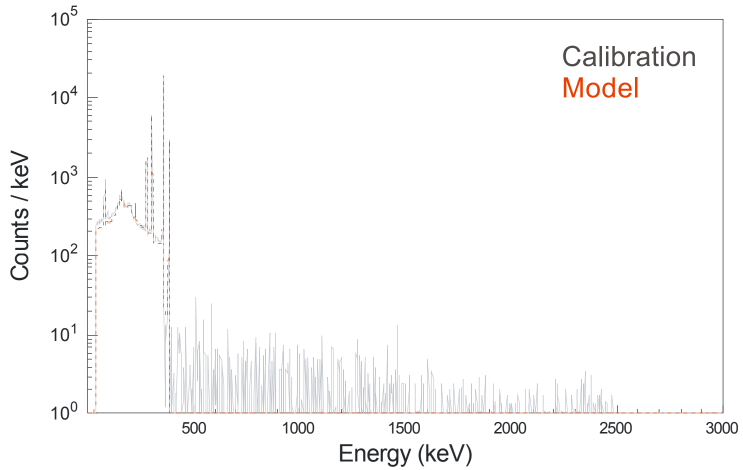
U232



Co60



Ba133



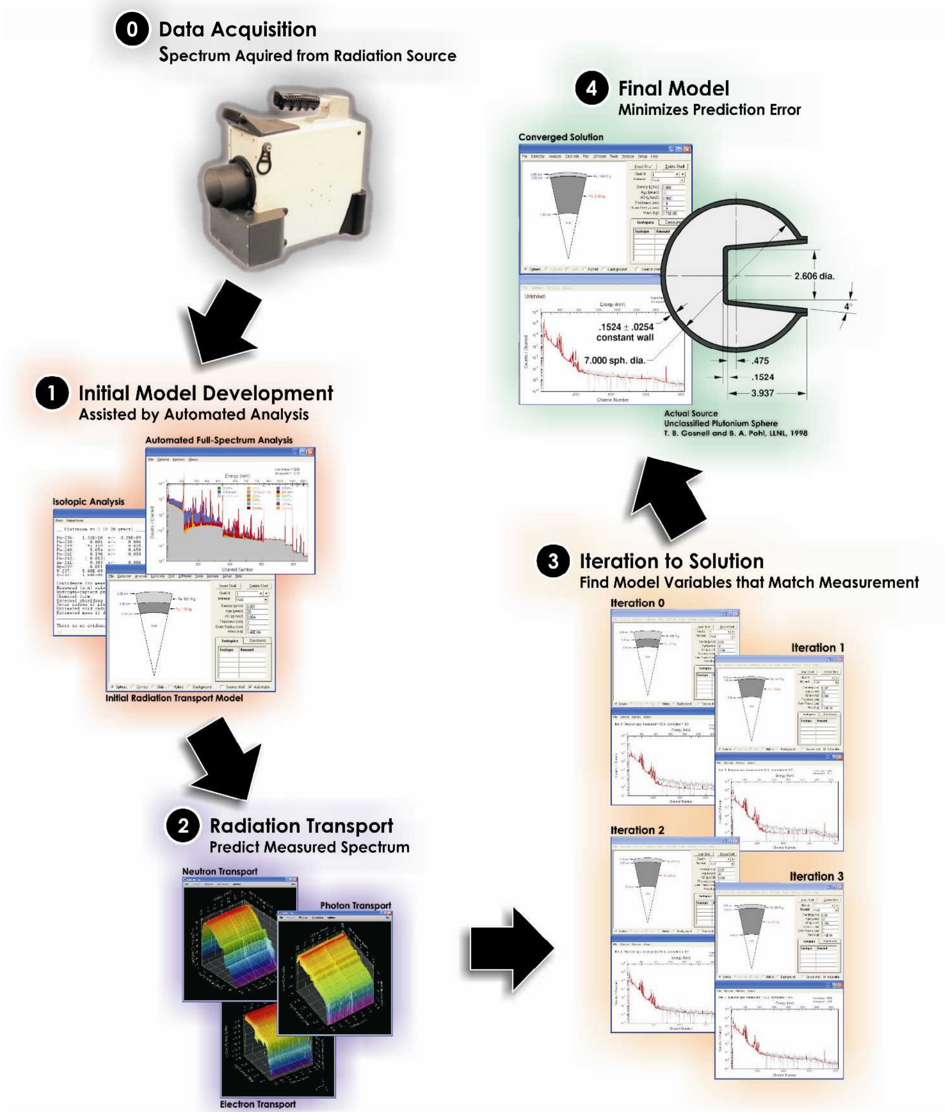
Nonlinear Optimization

- Minimize error between computed and measured detector responses
- Implementation uses χ^2 error metric: variance-weighted sum of squared errors; emphasizes response features with least uncertainty
- Empirical weighting scheme used to mix responses of different detectors in computation of χ^2
- Each iteration estimates gradient in χ^2 from small perturbations in each variable model parameter
- Levenberg–Marquardt algorithm used to seek model parameters that minimize χ^2

Example Problem and Solution

- Fit measured gamma spectrum and neutron count rate
- Initial guess:
  - Surface area & external shielding consistent with photopeak intensities
  - Mass consistent with neutron count rate (requires internal void)
- Shell dimensions treated as model variables
- Iterative optimization converges in about six steps
  - Each transport calculation executes in a few seconds
  - Each iteration requires about ten seconds
  - Solution obtained in about one minute
- Actual source was 2.4 kg plutonium metal sphere with conical section removed

Solution to Example Problem



Summary

- Possible to infer properties of unknown radiation source from measured detector responses using inverse transport approach
- Approach employs model-based iterative approach to determine source characteristics consistent with measured detector responses
- Enables detection, identification, and characterization of special nuclear materials for nonproliferation and international security