Technology Development for Safeguards Applications

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Nuclear Safeguards

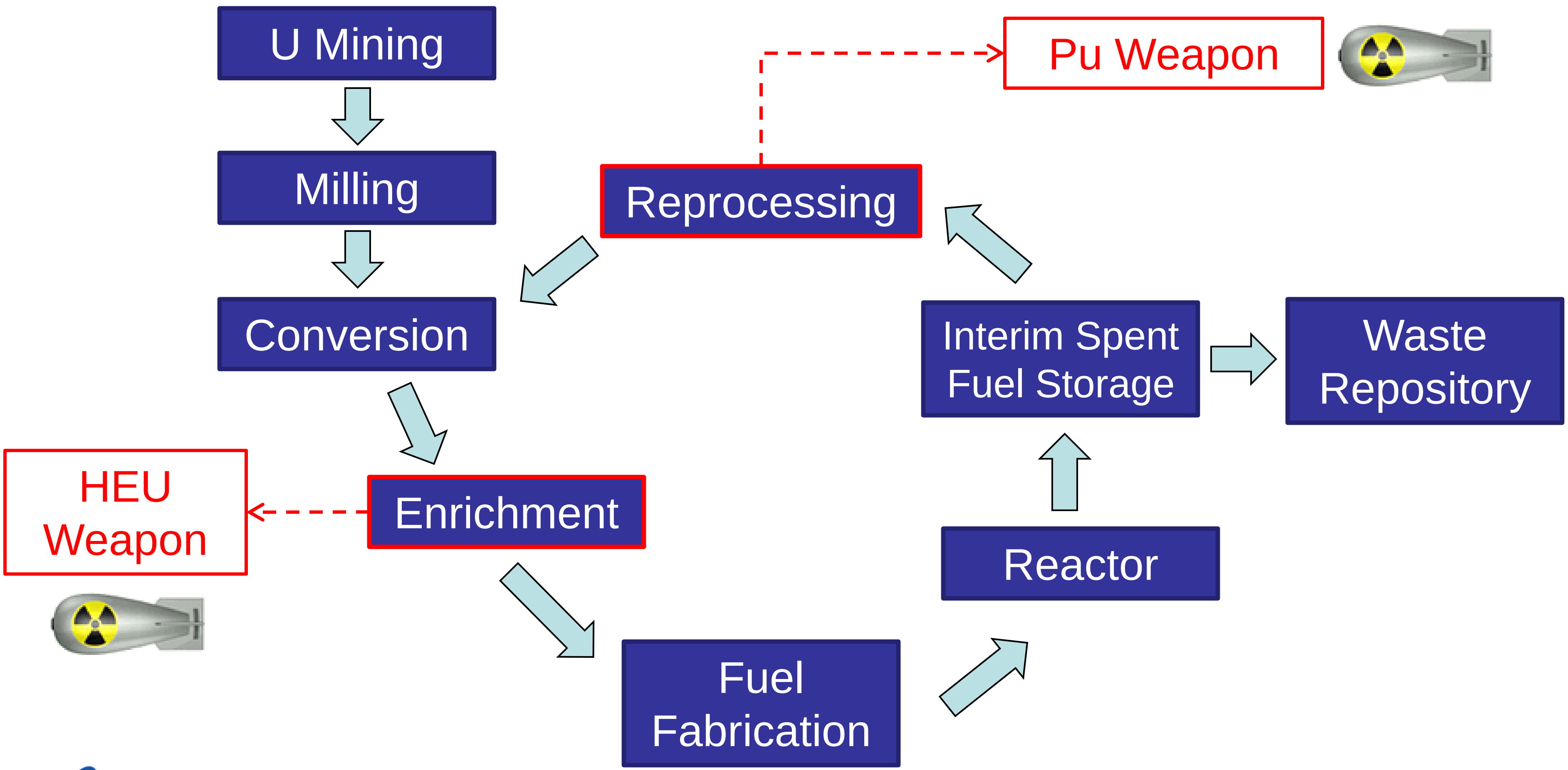
- Definition: a system of accounting and verification designed to ensure that nuclear material is not diverted for weapons purposes
- International safeguards:
  - Defined in Article III of the Nuclear Nonproliferation Treaty (NPT)
  - Verified by the International Atomic Energy Agency (IAEA)
- Regional safeguards:
  - Regional System of Accounting and Control (RSAC)
  - Examples: EURATOM (European Union), ABACC (Argentina & Brazil)
- Domestic safeguards:
  - State System of Accounting and Control (SSAC)
  - Example: JSGO (Japan)
- R/SSACs lay the foundation for international safeguards

Technology Development for Safeguards

Compliance with safeguards obligations ← **Technology** connects the two → **Verification** of compliance

- This lecture will focus on technology development for safeguards applications:
  - Specifically for uranium enrichment plants

The Nuclear Fuel Cycle



Uranium Enrichment Plants Worldwide

- Nuclear weapons states:
  - USA, Russia, UK, France, China
- Non-nuclear weapons states:
  - Argentina, Brazil, Germany, Japan, Netherlands, Iran
- States outside the NPT:
  - India, Pakistan, North Korea

Detector Development Case Study:
UF_6 Cylinder Assay Using Passive Neutron Detection

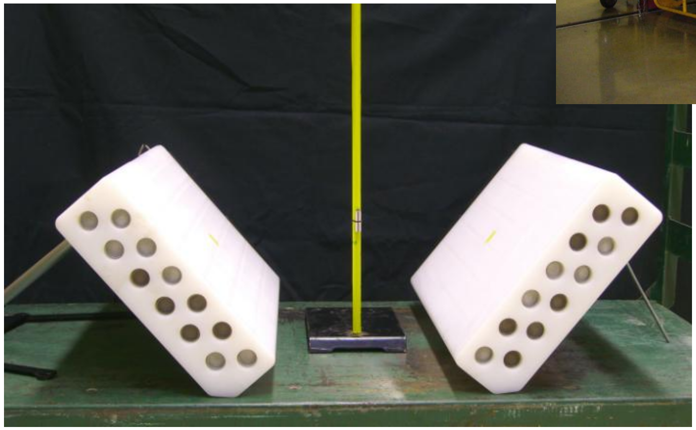
- The nuclear material at centrifuge enrichment plants is in the form of uranium hexafluoride (UF_6)
- If you don't know what you've got, how do you know if anything is missing?
  - At any given time, the majority of UF_6 is contained in 30-in. and 48-in. diameter storage cylinders
  - We need to verify the uranium mass and enrichment in those cylinders
  - We use this information to do the material balance over the plant

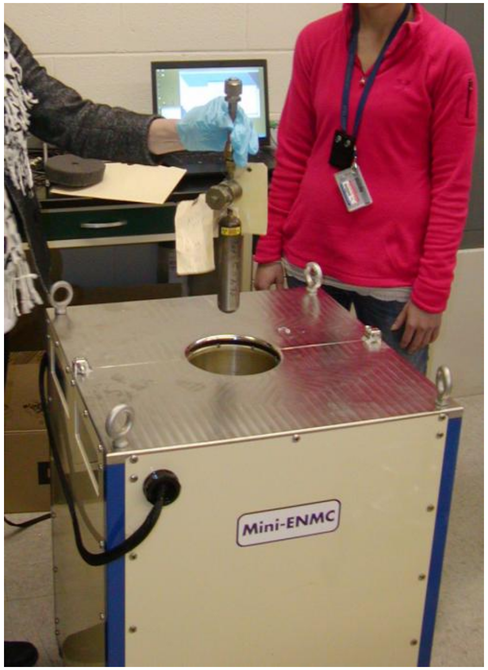
Traditional Methods for Larger Plants

- Current methods designed for smaller throughput plants:
  - Need more accuracy
  - Need near-real-time measurements
  - Strained human resources at IAEA
- Electronic scale for mass:
  - Maintenance and authentication issues
  - Doesn't show that what is being measured is nuclear material
- Gamma-ray measurement for uranium enrichment:
  - Very small sample volume (heterogeneous mixtures a problem)
  - Difficult to use in unattended mode

Passive Neutron Instruments

- Uranium Cylinder Assay System (UCAS)
- Passive Neutron Enrichment Meter (PNEM)
- Mini-Epithermal Neutron Multiplicity Counter (Mini-ENMC)

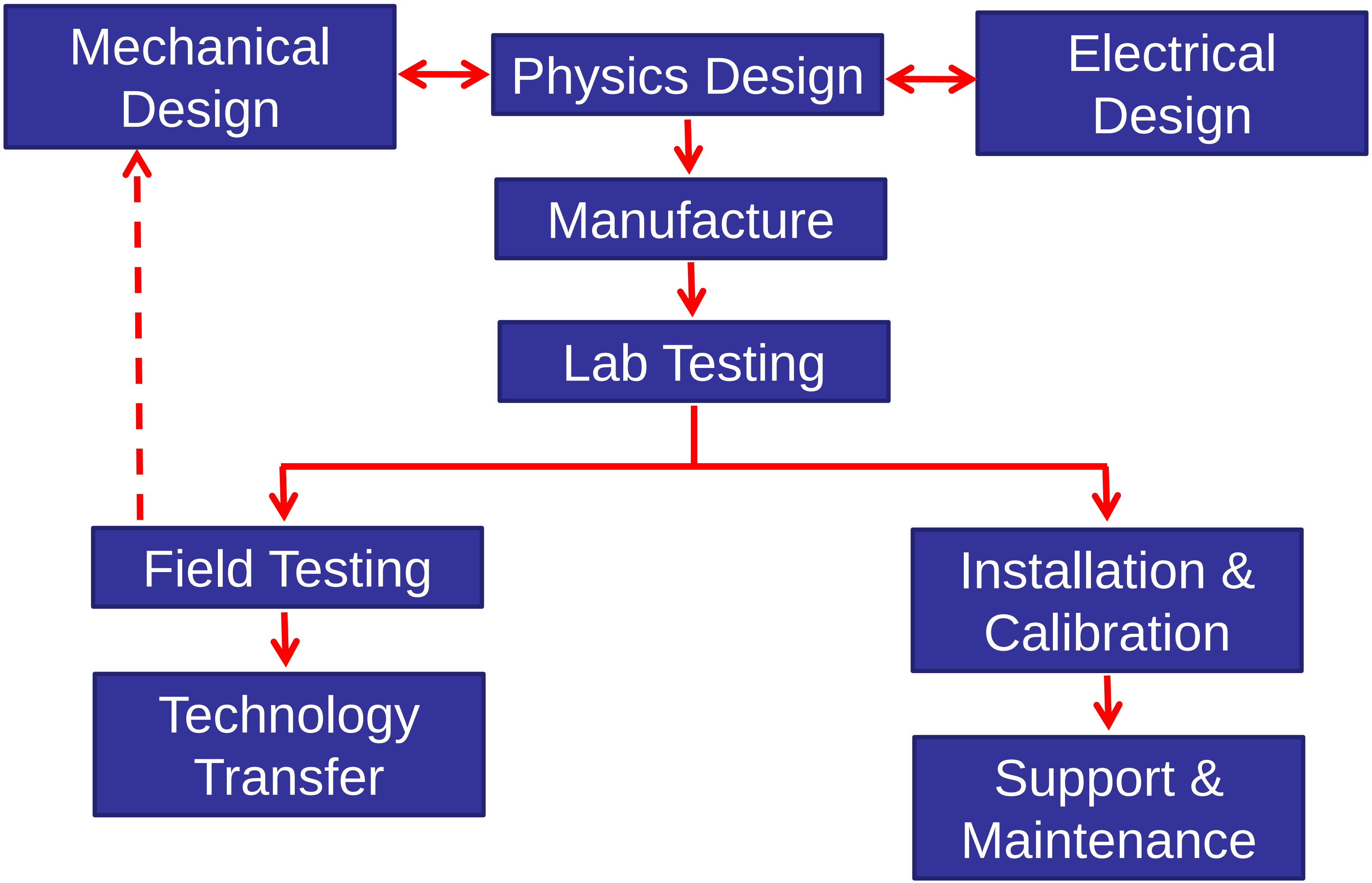




It Takes a Village… to Build a Detector

- Physicists
- Technicians
- Mechanical engineers
- Electrical engineers
- Project managers
- Software developers
- Facility operations
- Manufacturers
- Material suppliers
- Source custodians
- Radiation protection
- Administrative support
- Contractors
- Etc.

The Process


Mechanical Design
Physics Design
Electrical Design
Manufacture
Lab Testing
Field Testing
Technology Transfer
Installation & Calibration
Support & Maintenance

Physics Design

- What attributes are we trying to determine?
  - Uranium mass & enrichment
- What kind of neutron signatures can we measure?
  - Correlated vs. random?
  - Spontaneous fission, induced fission, (alpha,n) neutrons
- What type of detector should we use?
  - Passive vs. active?
  - Helium-3, fission chamber, liquid scintillator, etc.
- What else is in the bag of tricks?
  - The "poor man's spectrometer"
  - Ring ratios, front-to-back ratios, cadmium ratios
- We use modeling & simulation to test the physics design

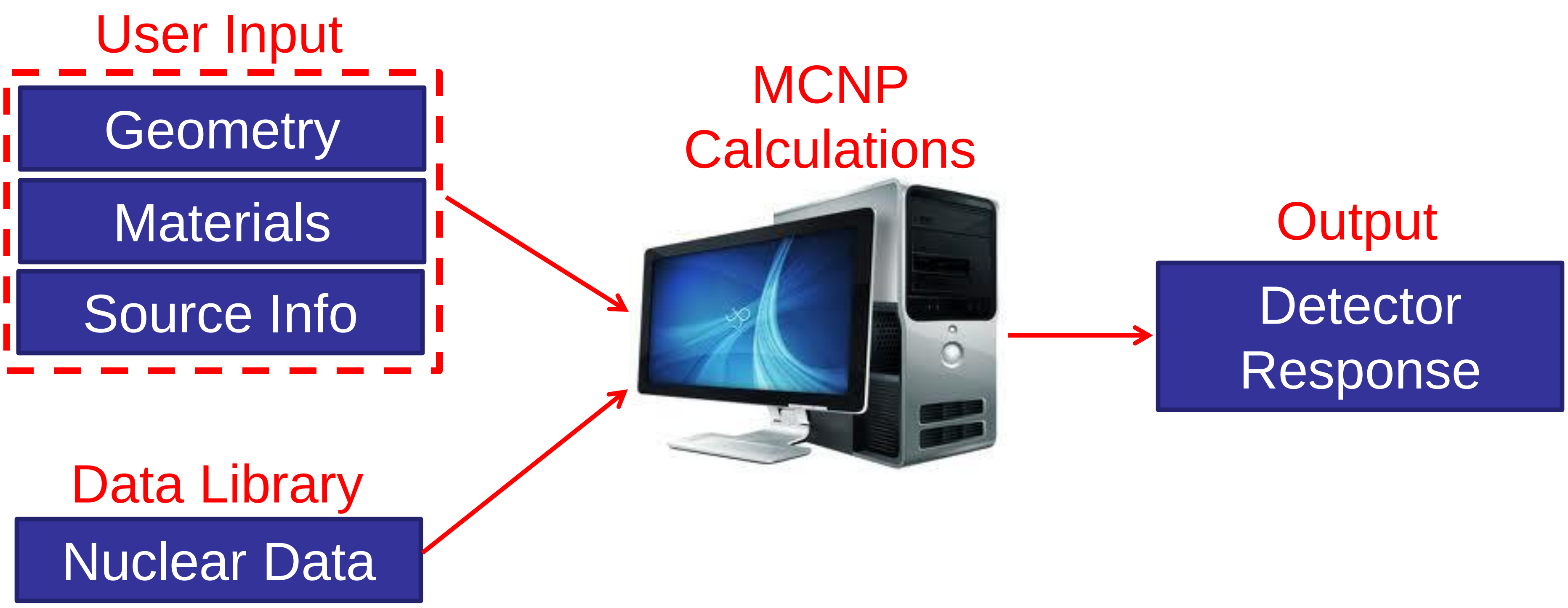
Modeling & Simulation

- We can predict physics phenomenon by two methods:
  - Experimental investigation (expensive, time consuming, sometimes impossible)
  - Theoretical calculation
- We can write down a mathematical “model” (equation) for some physical phenomena:
  - Calculate speed (i.e., distance/time): $v = \frac{x}{t}$
  - Slightly more complicated to describe neutron behavior:

$$\frac{1}{v(E)}\frac{\partial\psi(\vec{r},E,\vec{\Omega},t)}{\partial t} = -\vec{\Omega}\cdot\vec{\nabla}\psi(\vec{r},E,\vec{\Omega},t) - \sigma_t(\vec{r},E)\psi(\vec{r},E,\vec{\Omega},t)$$
$$+\int_0^\infty dE' \int_{4\pi} d\Omega' \sigma_s(\vec{r},E' \to E,\vec{\Omega}' \to \vec{\Omega})\psi(\vec{r},E',\vec{\Omega}',t) + S(\vec{r},E,\vec{\Omega},t)$$

Modeling & Simulation

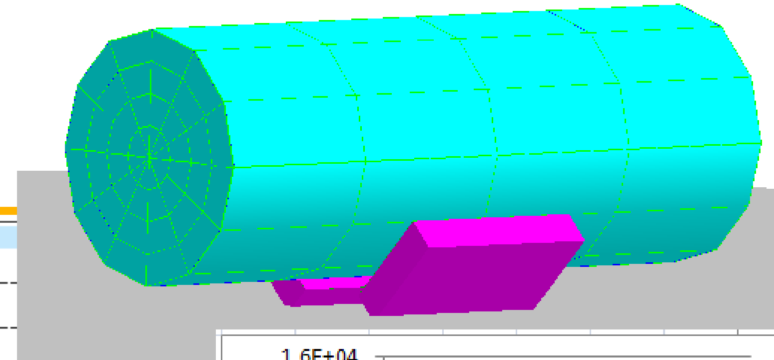
- We can solve this equation using codes such as MCNP to predict the count rate in our detector (detector response):



Modeling & Simulation

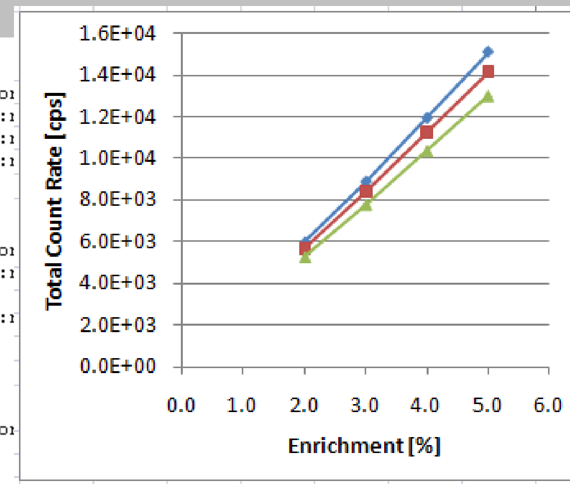
- Does the detector behave as we expected?
  - Example: Increase in count rate with increase in UF_6 mass?
- Optimization:
  - Maximize count rate (to minimize statistical uncertainty)
  - Maximize leverage (how much does the count rate increase?)
- Performance calculations:
  - Predict the minimum detectable mass
  - Predict random & systematic uncertainties
- Sensitivity studies:
  - Change one parameter to see its effect on the results
  - Example: How does the count rate change if the density of UF_6 is: 4.7 g/cm^3, 4.8 g/cm^3, 4.9 g/cm^3, 5.0 cm^3, 5.1 g/cm^3, 5.2 g/cm^3, etc.

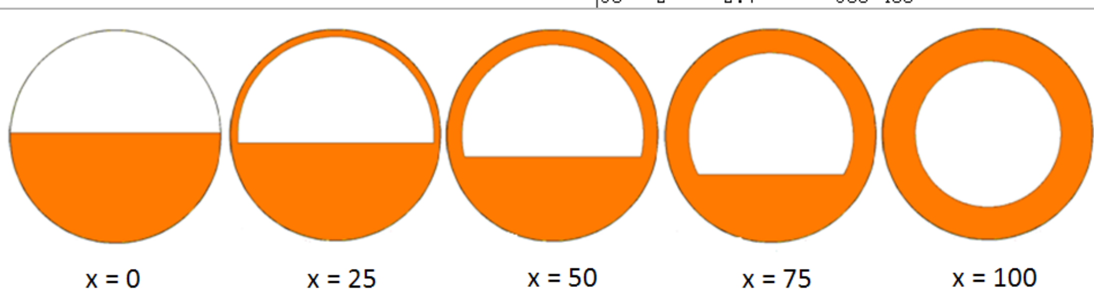
Modeling & Simulation



4.0% Enriched UF6			
	Isotopic Composition		
	Isotope	Atom %	
	U-234	0.034430	
	U-235	4.00	
	U-238	95.965570	
ssume:	density (solid) =	5.09	g/cc
Given:	N(A) =	6.022E+23	atoms/mole
	M(U-234) =	234.0409456	g/mole
	M(U-235) =	235.0439231	g/mole
	M(U-238) =	238.0507826	g/mole
	M(F) =	18.9984032	g/mole
lations:	M(U) =	237.9291276	g/mole
	M(UF6) =	351.9195468	g/mole
	N(UF6) =	8.709940E+21	molecules/cc
	N(U) =	8.709940E+21	atoms/cc
	N(U-234) =	2.998832E+18	atoms/cc
	N(U-235) =	3.483976E+20	atoms/cc
	N(U-238) =	8.358543E+21	atoms/cc

```
Passive Neutron Enrichment Meter
c
c -----------------------------------------------
c                   CELL CARDS
c -----------------------------------------------
c
c *** 30B UF6 Cylinder ***
c
c   mat    den        surfaces                                impo
10   8     -5.09      -100  102                               imp:
11   6     -0.001204  -102                                    imp:
12   7     -7.84       100 -101                               imp:
c
c *** Detector Dummy Boxes ***
c
c   mat    den       surfaces                    universe     impo
98   0               -201 -205                    fill=1       imp:
    *trcl=(0 12.0 -42.57 0 90 90 90 45 -45 90 135 45)
99   0               -201 -205                    fill=1       imp:
    *trcl=(0 -12.0 -42.57 -180 90 90 90 135 45 90 45 -45)
c
c *** Moderator ***
c
c   mat    den       surfaces                    universe     impo
20   3     -0.96     -200 300 301 302 303 304 305
                      500 501 502 503 504 505 310
                      311 312 313 314 315 510 511
                      512 513 514 515 -204          u=1     imp:n=1  $ polyethylene block
21   4     -8.65     200  202 -203 -204             u=1     imp:n=1  $ side Cd cover
22   4     -8.65     200 -202 -203 -204             u=1     imp:n=1  $ Cd liner on inner poly wall
23   6   -0.001204   200  203                       u=1     imp:n=1  $ Bare system / air space on top of poly
24   4     -8.65     204                            u=1     imp:n=1  $ Cd liner on angled surface
c
c *** He-3 Tubes ***
c
c --- Top Row ---
c
c   mat    den       surfaces                    universe     importance
30   2     -2.7      -300 400                       u=1     imp:n=1  $ T1 aluminum He-3 tube
                                                    u=1     imp:n=1  $ T2 aluminum He-3 tube
                                                    u=1     imp:n=1  $ T3 aluminum He-3 tube
                                                    u=1     imp:n=1  $ T4 aluminum He-3 tube
                                                    u=1     imp:n=1  $ T5 aluminum He-3 tube
                                                    u=1     imp:n=1  $ T6 aluminum He-3 tube

                                                 universe     importance
                                                    u=1     imp:n=1  $ T1 He-3 fill
                                                    u=1     imp:n=1  $ T2 He-3 fill
                                                    u=1     imp:n=1  $ T3 He-3 fill
                                                    u=1     imp:n=1  $ T4 He-3 fill
                                                    u=1     imp:n=1  $ T5 He-3 fill
```





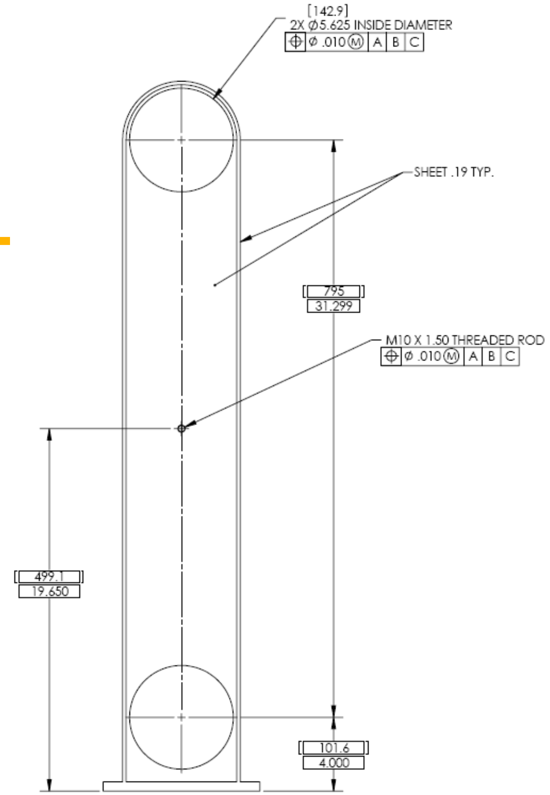
Modeling & Simulation

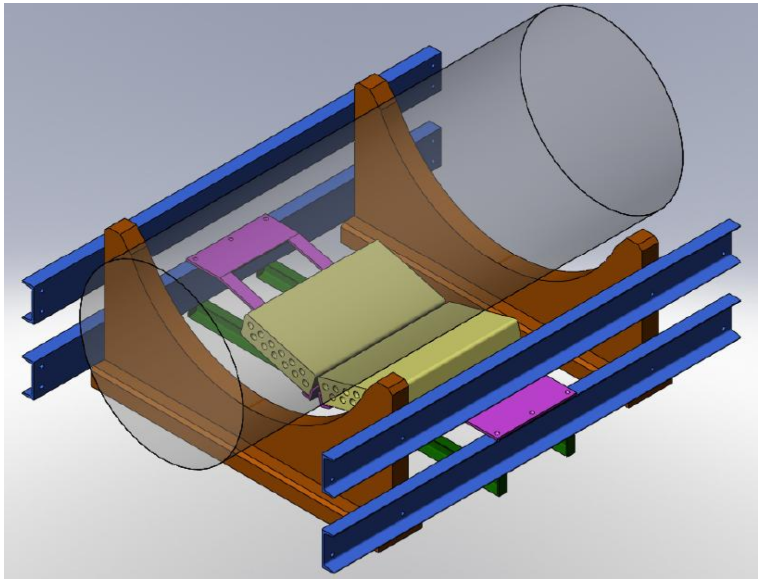
- Accurate predictions require good nuclear data, which we don't always have!
- Example: F(alpha,n) source strength in UF_6
  - The predicted count rate is proportional to the source strength
  - Large discrepancies between values cited in various locations

Isotope	w/o	mass [g]	SOURCES 4C n/g-sec	PANDA n/g-sec	Walton n/g-sec	Samson n/g-sec	UCAS n/g-sec
U-234	0.0337	4.73E+02	-	5.80E+02	4.60E+02	5.76E+02	4.53E+02
U-235	3.8527	5.40E+04	-	8.00E-02	8.80E-02	8.20E-02	8.80E-02
U-238	96.1136	1.35E+06	-	2.80E-02	9.50E-03	1.36E-02	9.50E-03
Total Source Strength (a,n)+SF [n/sec]:			3.11E+05	3.16E+05	2.35E+05	2.95E+05	2.31E+05
% Difference from Samson:			**5.59**	**7.18**	**-20.35**	**-**	**-21.52**

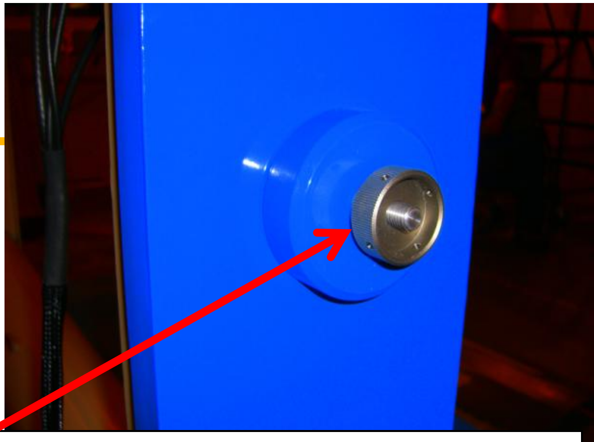
Mechanical Design

- What form factor will the detector be?
  - Slab, well counter, box counter
- Does the system need to be portable?
- Are there size and weight constraints?
- How will the detector interface with the plant?
- Are there seismic considerations?
- Is the design concept manufacturable?
- Do cables need to be inside tamper-indicating conduit?

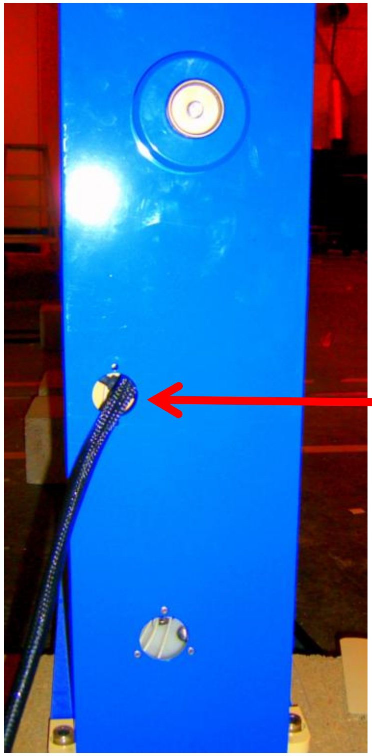




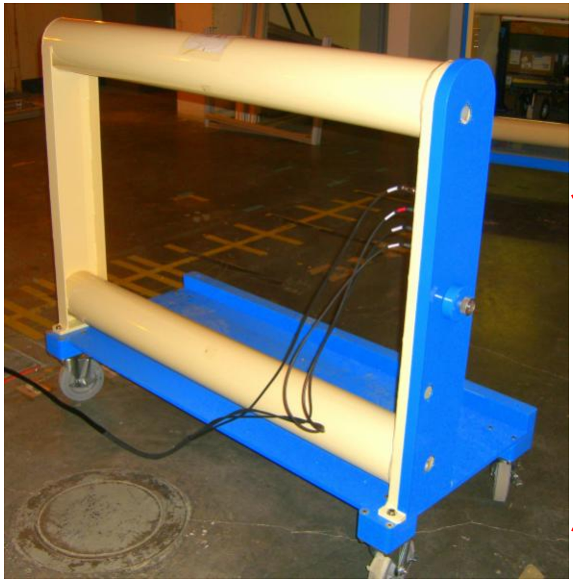
Mechanical Design:
Accommodating a Tamper-Indicating Device

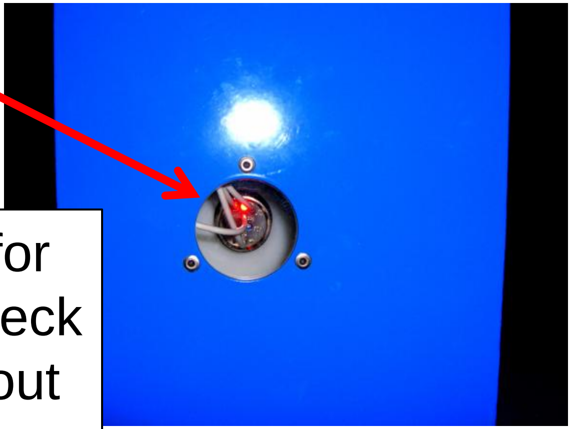


TID is threaded through the nut and bolt that hold the security cover in place



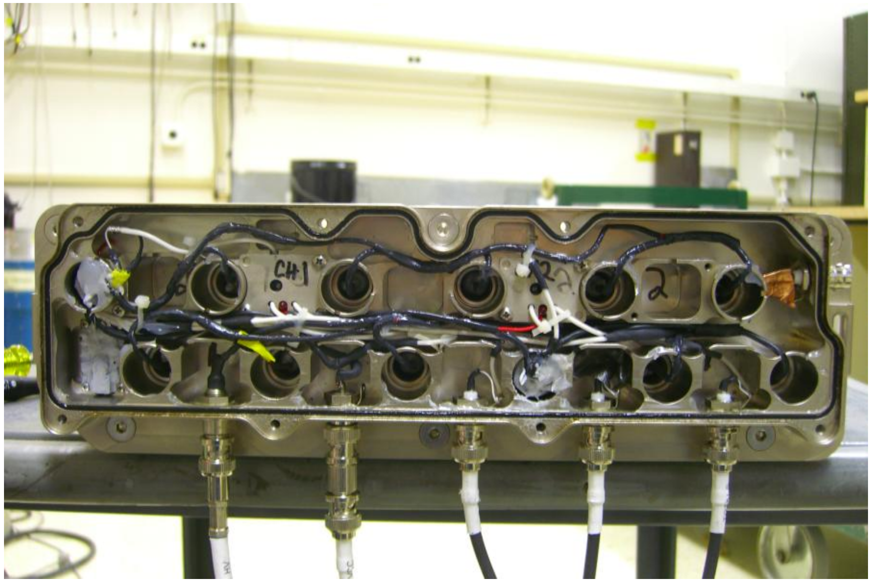
Cables connect to detectors inside of security cover





Window allows for state-of-health check on detector without removing the cover

Electrical Design



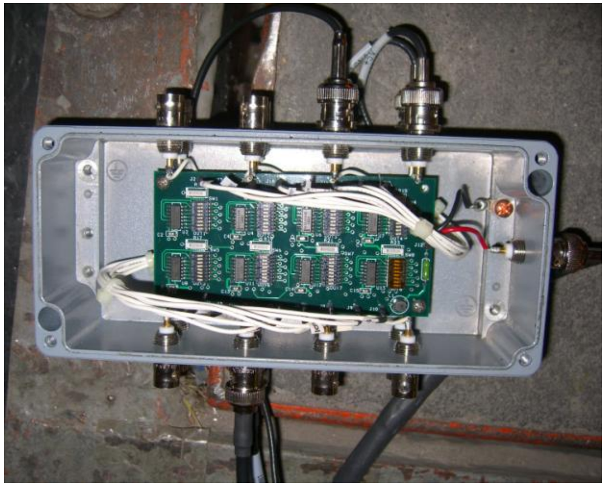
Commercial off-the-shelf amplifier

Custom designed amplifier

Electrical Design

Data acquisition:
shift register vs. list mode

OR box for signal splitting
and combination

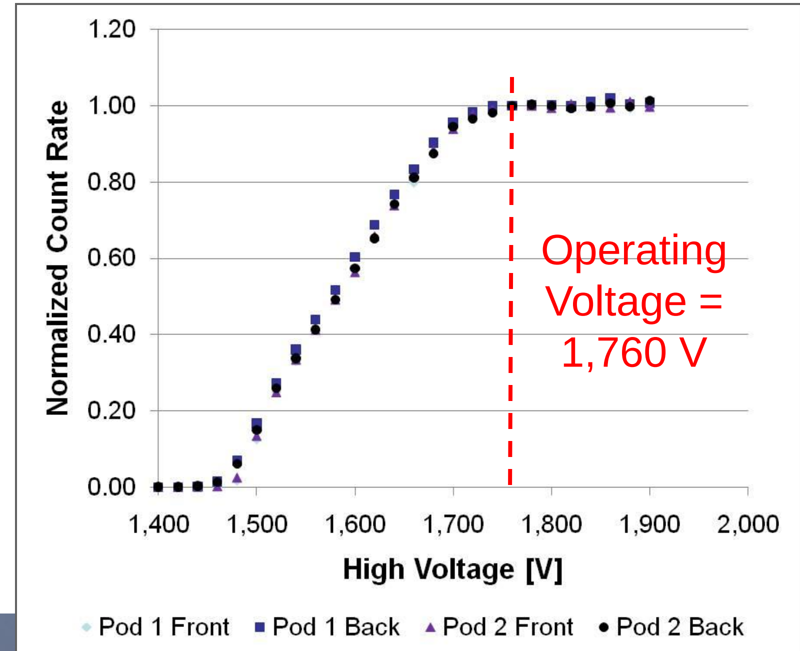


Electrical Design

- More considerations:
  - What are the power requirements?
  - Battery powered vs. plug in?
  - Will the HV to the tubes interfere with the detector signal?
  - Are you going to run a laptop or a PC?
  - What software will you run?
  - Are the cables going to interfere with plant operations?
  - Will radiation affect the electronics?
  - Will moisture & humidity affect the electronics?
  - How will you store the external electrical components?
  - Are the electrical components fire resistant?

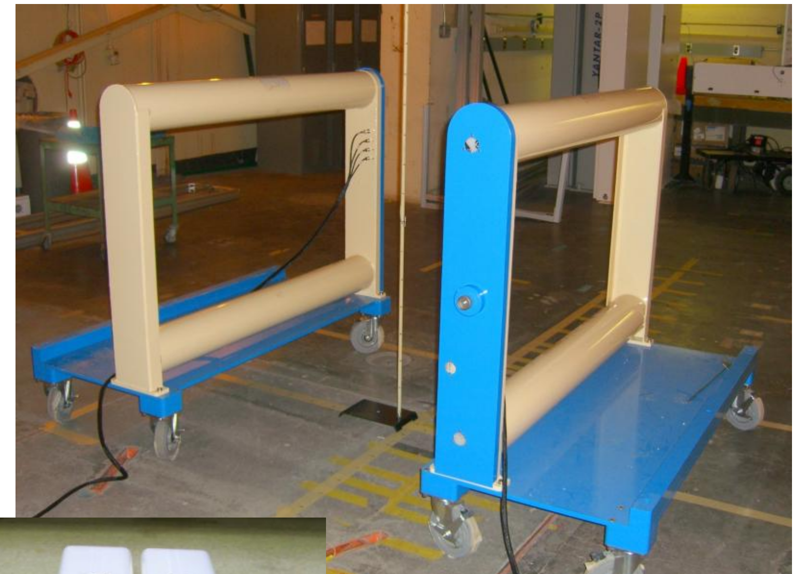
Lab Testing & Characterization

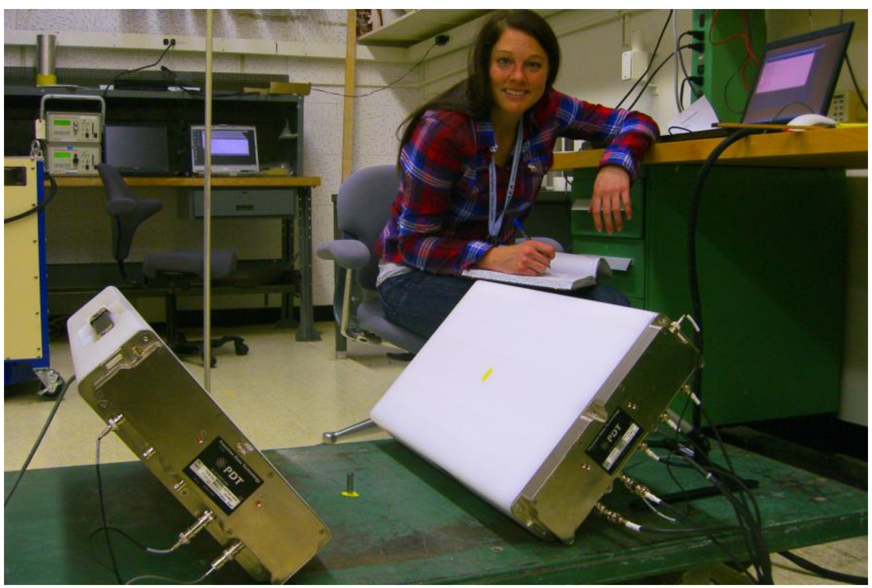
- Gain matching
- Voltage plateaus
- Stability & noise
- Sensitivity to:
  - Moisture
  - Temperature
  - RF background

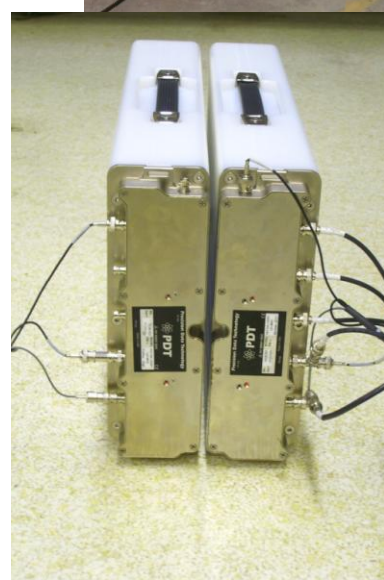


Lab Testing & Characterization

- Efficiency
- Die-away time
- Dead time
- MCNPX benchmark

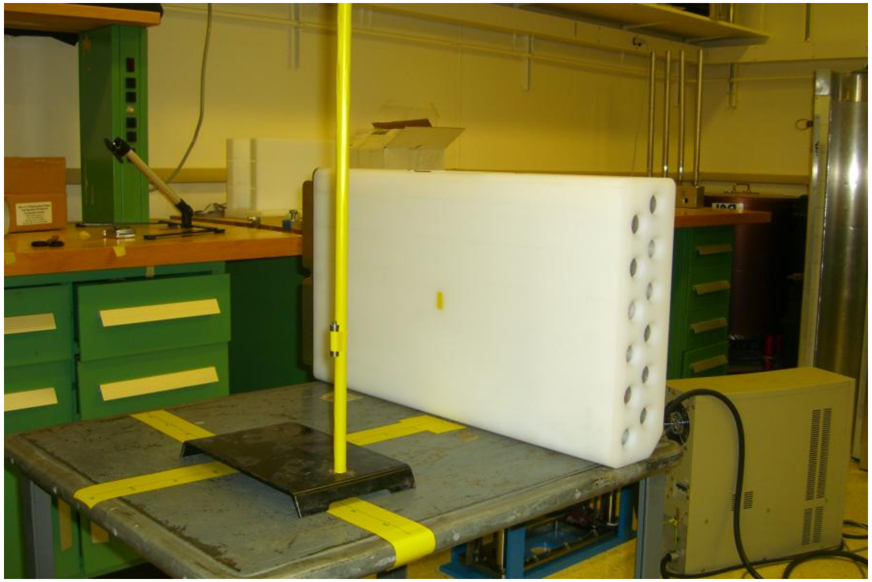




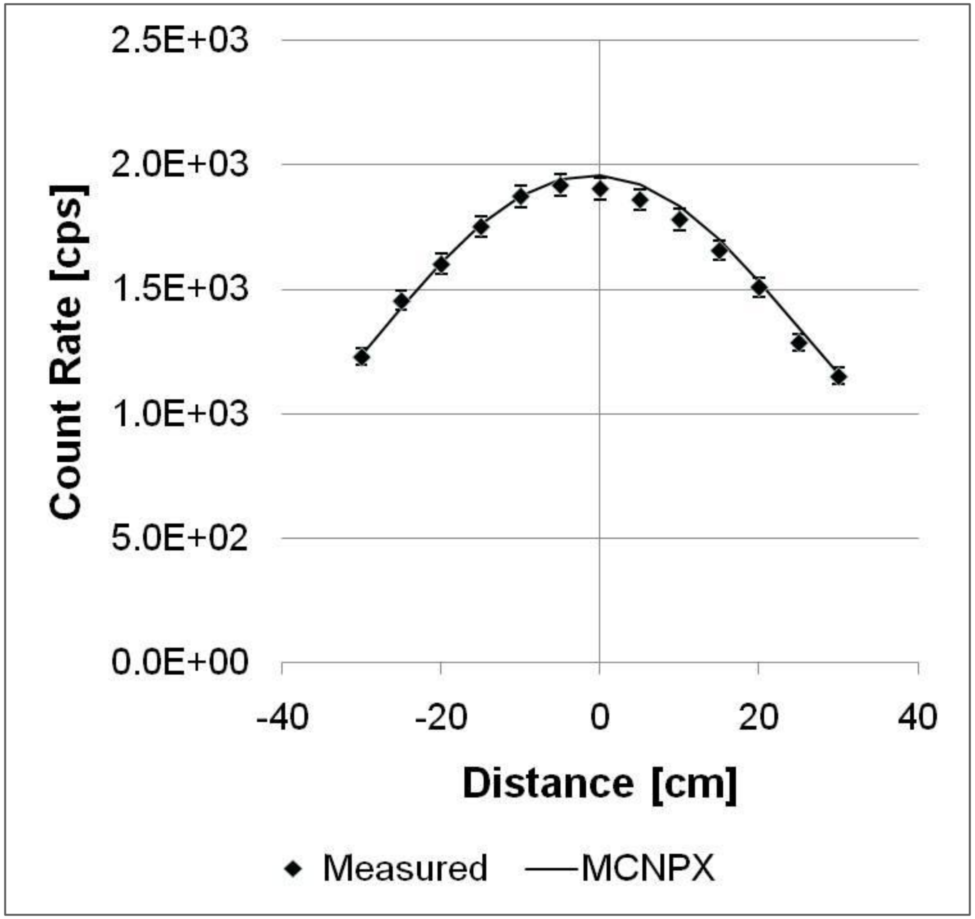


$$\tau = -\frac{G_1}{ln(D_2/D_1 - 1)}$$

Lab Testing & Characterization



Detector response profile: does the measured response match the modeled response?



Cylinder Measurements

Field Testing

Installation & Calibration

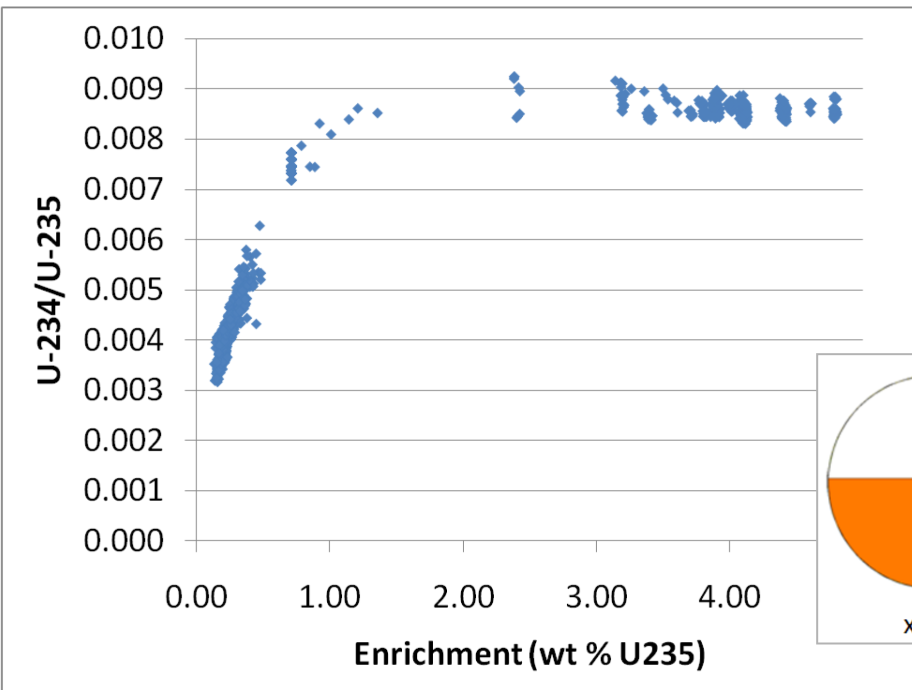
Cylinder Measurements

- Calibration standards:
  - Are there calibration standards available?
  - How well characterized are they?
- Data analysis:
  - Do the measurements match your models?
  - If not, why?

```
             Die away time:      50.0000
                Efficiency:       0.0001
     Multiplicity deadtime:       0.0000
    Coefficient A deadtime:       0.0000
    Coefficient B deadtime:       0.0000
    Coefficient C deadtime:       0.0000
     Doubles gate fraction:       0.0001
     Triples gate fraction:       0.0001

    Normalization constant:       1.0000 +-      0.0000
    Passive singles bkgrnd:       3.538 +-       0.006
    Passive doubles bkgrnd:       0.010 +-       0.000
    Passive triples bkgrnd:      -0.000 +-       0.000
    Passive scaler1 bkgrnd:       1.440
    Passive scaler2 bkgrnd:       2.132

     Number passive cycles:          20
          Count time (sec):          30

Passive messages

Passive calibration curve: failed stratum rejection limits

Passive results

                                  Singles:        2013.047 +-      1.641
                                  Doubles:           2.195 +-      0.952
                                  Triples:          -0.037 +-      0.231
                                    Quads:          -0.049 +-      0.055
                            Quads/Triples:           4.709 +-      3.673
                                 Scaler 1:        1014.360 +-      0.867
                                 Scaler 2:        1069.084 +-      0.964

 Passive calibration curve results

                           U238 mass (g):     1378187.873 +-   1382.123
                                U235 (%):           3.900
                           U235 mass (g):       55930.621 +-     56.090
                        Total U mass (g):     1434118.494 +-   1383.261
                  Declared U235 mass (g):       54618.000
        Declared - assay U235 mass (g):        -1312.621 +-     56.090
        Declared - assay U235 mass (%):           -2.403 +-      0.103

Passive calibration curve calibration parameters

                          Equation:  S = a + b * m + c * m^2 + d * m^3
                                  a:    0.000000e+000
                                  b:    1.734080e-003
                                  c:   -1.984000e-010
                                  d:    0.000000e+000
```

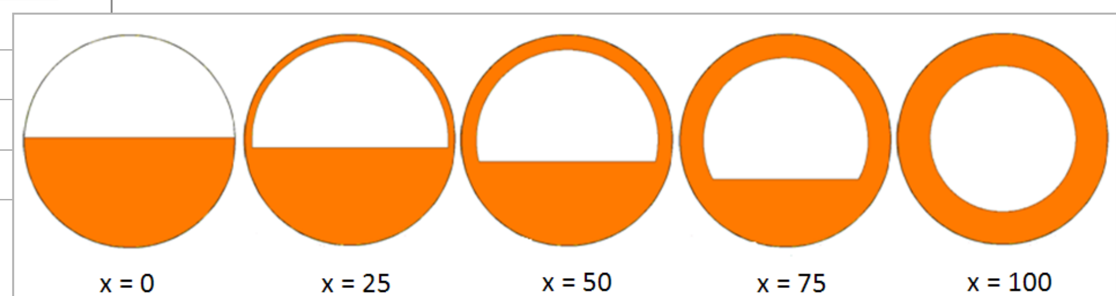
Systematic Uncertainty

- Can lead to measurement bias
- Difficult to determine without a lot measurements



U-234 content as a function of enrichment

UF_6 distribution inside the cylinders



Stakeholders

- You must be able to talk to many different stakeholders and interested parties about the technology

- Facility operators
- Domestic & regional safeguards authorities

- DOE officials
- Industrial partners
- Other labs

Stakeholders

- Press

- IAEA officials
- State Dept officials

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Keeping tabs. Japan's Rokkasho reprocessing plant is testing new equipment (*inset*) for measuring the amount of uranium it handles.

technique, they count neutrons that the rods emit both spontaneously and through induced fission. The spontaneous emissions

research and development that could help with secret weapons-building plans. For example, says Richard Wallace, a former IAEA analyst who now works at LANL, "you could have a country that says it is not working to reprocess spent fuel from nuclear reactors—and then you may go into the literature and find papers dis-

Conclusions

- Technology is the bridge that connects compliance and verification with safeguards obligations
- Developing new technologies for safeguards applications is a process that involves a highly multidisciplinary team of people
- Example: uranium enrichment plant safeguards
  - UF_6 cylinder assay using passive neutron detection
  - Systems: UCAS, PNEM, and the Mini-ENMC
- There are still many challenges to overcome

Questions?