Mathematical efficiency models and system calibrations

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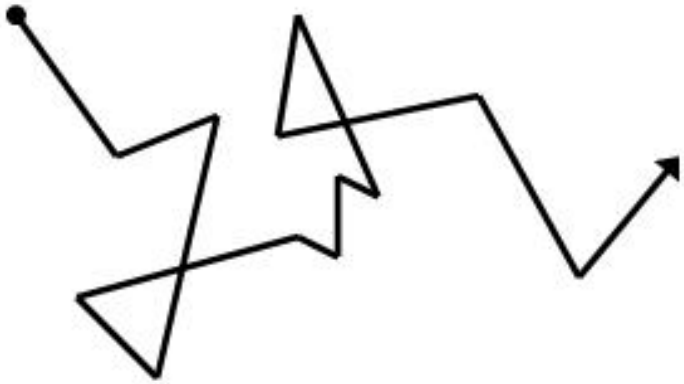
Outline

- MCNP
- ISOCS
- Uses of mathematical efficiencies
- Examples
- Conclusion

MCNP

- Monte Carlo N-Particle (MCNP) code
- Simulations transport :
  - Charged particles (electron/positron, alpha/heavy ions)
  - Photons (gamma rays, X-rays)
  - Neutrons
- Physics processes include:
  - Photoelectric effect
  - Compton scattering
  - Pair production
  - Bremsstrahlung
  - Electromagnetic stopping/scattering
  - Nuclear stopping/scattering
- Simulation is stochastic
  - Random walk from beginning of particle creation to end
  - Sample events according to their natural probabilities



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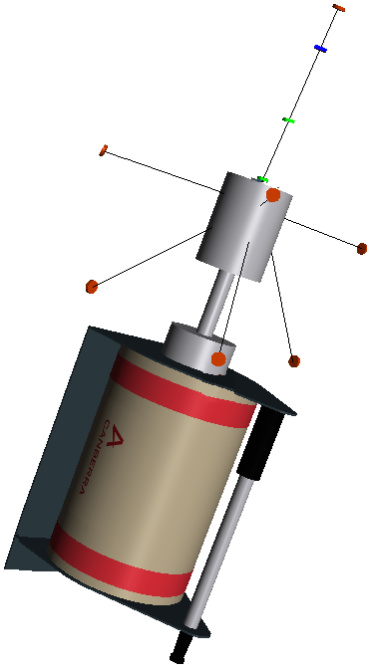
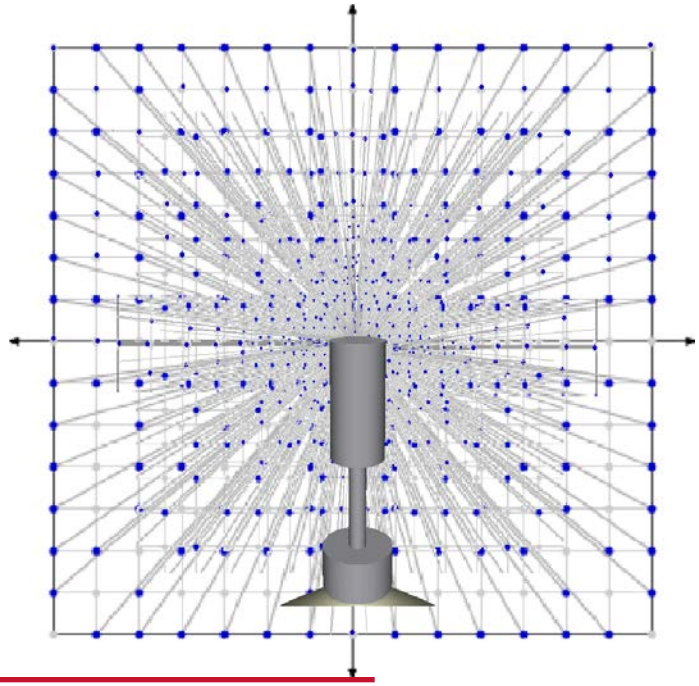
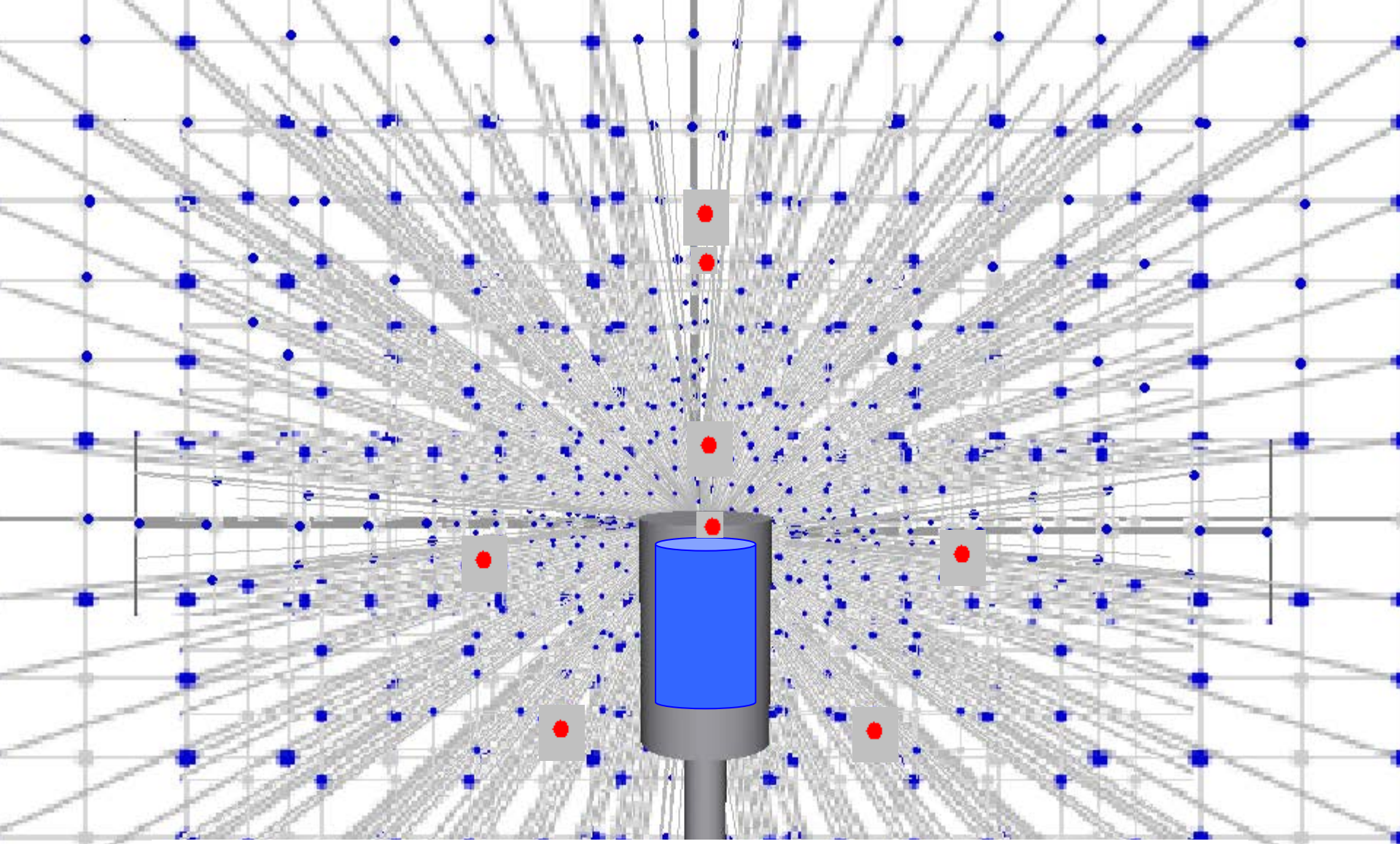
ISOCS (In Situ Object Counting System)

- **Characterize the detector**
  - **Series of controlled measurements at various positions**
    - 10 NIST-traceable multi-energy point source measurements
    - Source uncertainty = 3.1% at 99% confidence level
  - **MCNP model of detector created and validated by sources**
  - **Generate a grid of efficiency points in space**
- **Result is a rigorously validated mathematical model of the detector that can be extended to a variety of geometries**







- Total number of ISOCS characterizations > 3700
- Number of ISOCS verify > 550
- Number of technical reports supporting ISOCS > 100

Uses of mathematical efficiencies

- **Initial design – Steer the preliminary design in the correct direction before building a prototype**
- **Uncertainty analysis – Investigate the effects of geometrical uncertainty on the primary calibration**
- **Nuclide extension – Determine efficiencies for nuclides that are not practical to obtain in a standard**
- **Primary calibration aid – Give confidence in a primary calibration measurement**
- **Primary calibration – using a benchmarked model**

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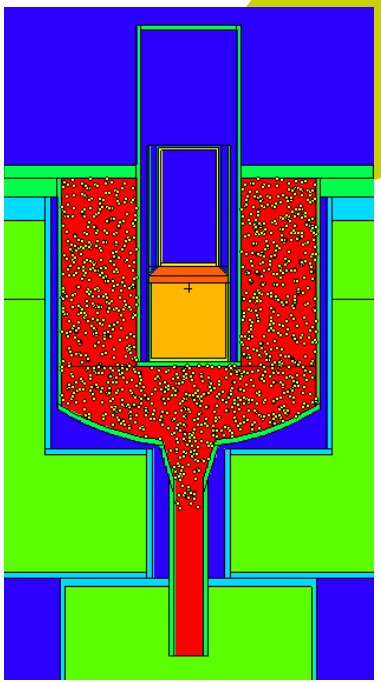
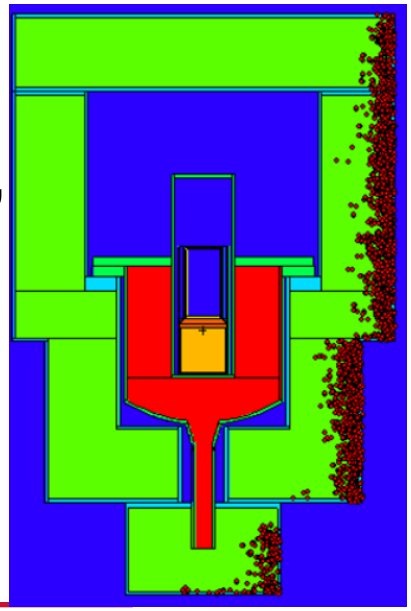
Initial Design of a measurement system

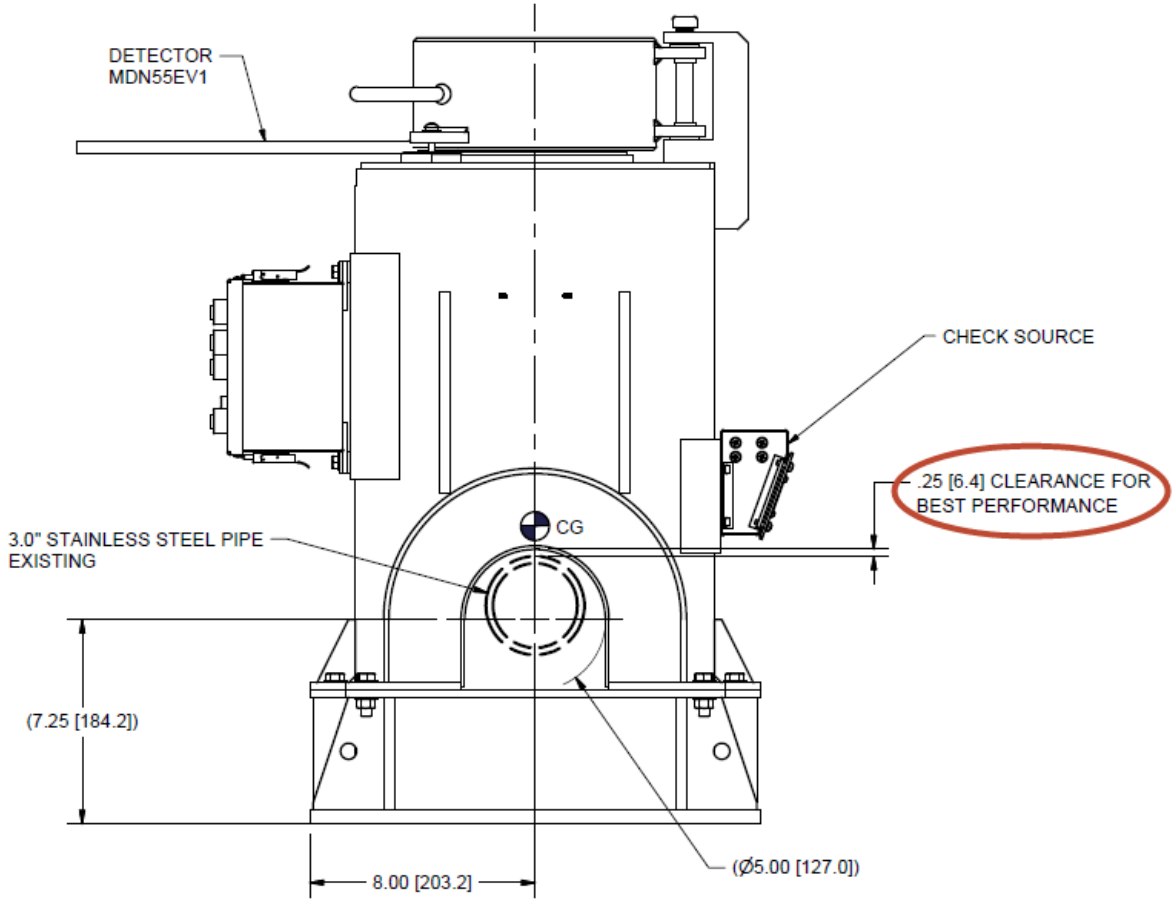


- When a customer supplies a hard set of performance criteria and the new system will be designed from scratch or a design is modified – mathematical efficiencies can help
- Obtain rough estimate of efficiency (typically within 20% even for a “rough model”)
- Obtain an estimate of shielding effectiveness in worst case background conditions
- Calculate Minimum Detectable Concentration (MDA), response time, TID to critical components…
- Do all this without building a prototype



Uncertainty analysis

- Use simulations to determine the effect of design tolerances on the Total Measurement Uncertainty (TMU)
- Some examples:
  - Detector positioning
  - Pipe installation
  - Pipe wall thickness
  - Gas pressure/density
- Make multiple models
  - Model each dimension
  - Use max and min
  - Find range of efficiency
  - Sum all in quadrature



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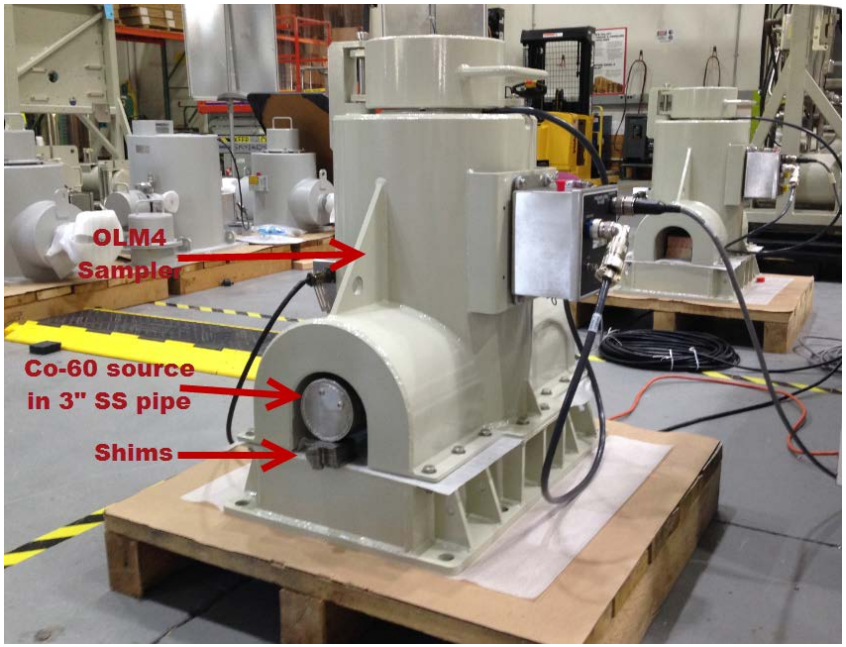
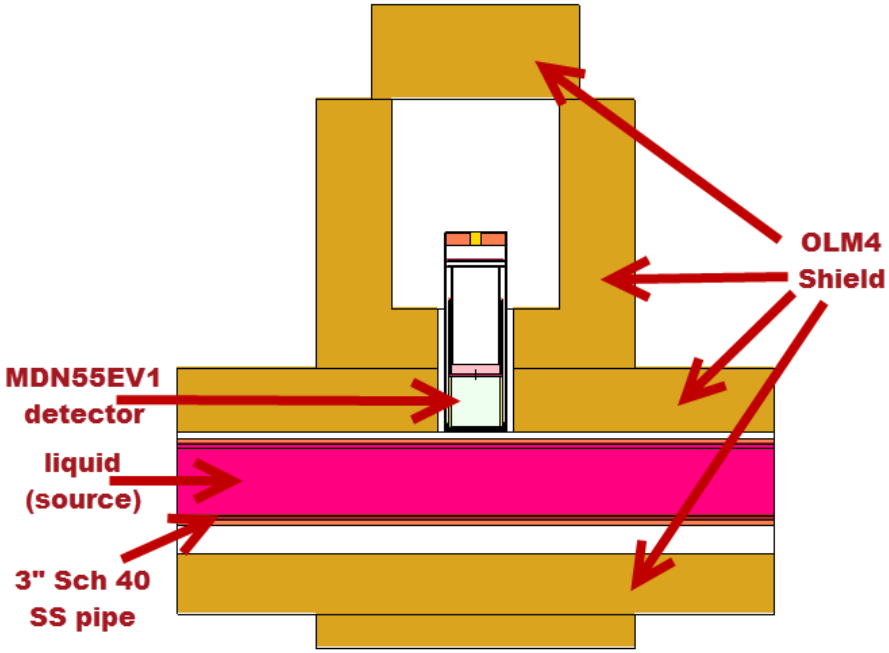
Nuclide or geometry extension

- **Many nuclides (or geometries) of interest are impractical for calibration sources**
  - **Short half life**
  - **Extremely large geometry**
- **Use simulations to determine the efficiency after a proper benchmark**





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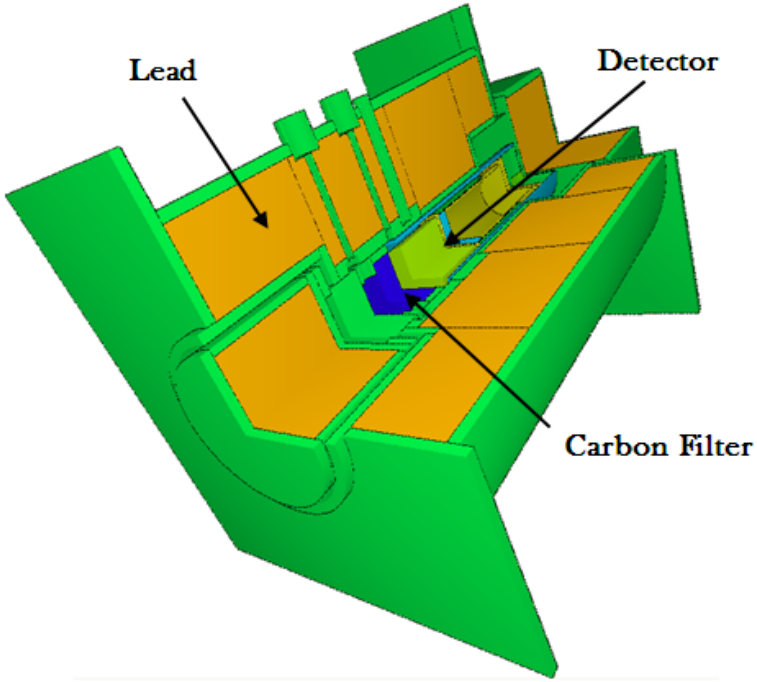
Primary calibration aid

- **Provide a check of the primary calibration measurement**
  - **The modeled efficiency and the measured should agree**
  - **Improves confidence in the calibration**



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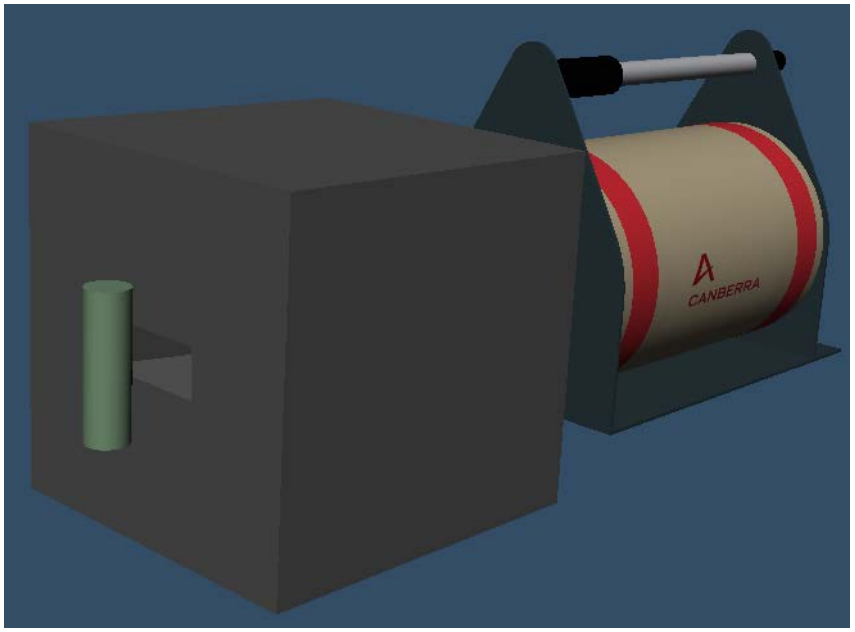
Primary Calibration

- **ISOCS (In Situ Object Counting System)**
  - **MCNP model of the detector based on numerous measurements**
- **Use model efficiency to generate primary calibration**
- **Confirm modeled efficiency with a verification measurement that includes many gamma energies**



Nuclide	Gamma-Ray Energy (keV)	Half-Life, Days
Am-241	59.5	157860
Cd-109	88.0	462.60
Co-57	122.1	271.79
Ce-139	165.9	137.6
Cr-51	320.1	27.70
Sn-113	391.7	115.1
Sr-85	514.0	64.84
Cs-137	661.7	10983
Mn-54	834.9	312.1
Y-88	898.0	106.6
Zn-65	1115.6	244.3
Co-60	1173.2	1925.4
Co-60	1332.5	1925.4
Y-88	1836.1	106.6

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Some examples

- Spectroscopic Noble gas stack monitor – ISOCS
- Gaseous Fission Product monitor– ISOCS
- On-line liquid monitor – MCNP
- In-line liquid monitor – MCNP
- N-16 monitor – MCNP
- Iodine monitor – MCNP
- Noble gas monitor - MCNP
- Environmental gamma monitor – MCNP
- Sr-90 water monitor - MCNP

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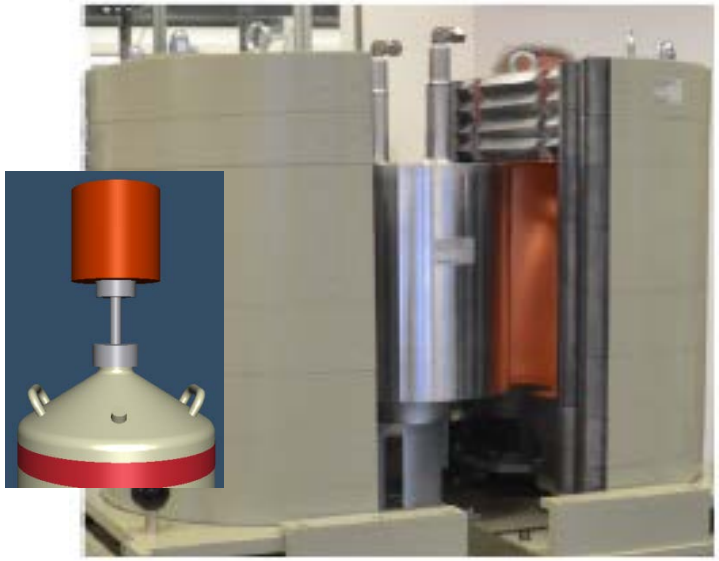
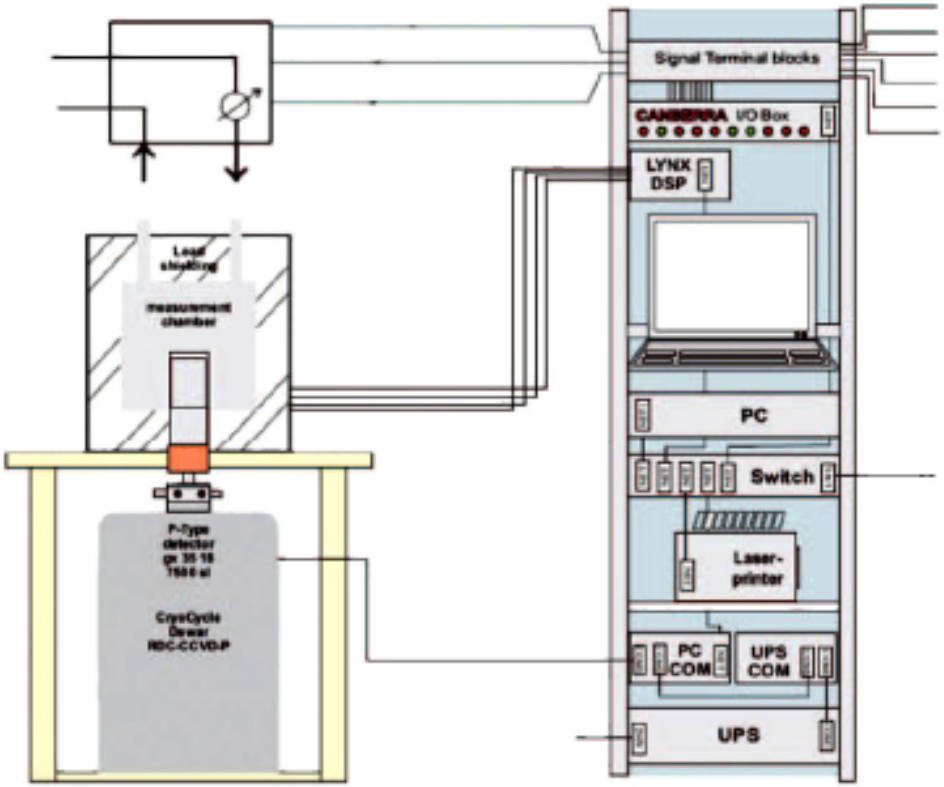
Spectroscopic noble gas monitor

- Stack monitor (noble gas)
- Shielded Marinelli beaker
- HPGe with Cryo-cycle
- ISOCS calibration with verification measurements
- Following KTA methodology





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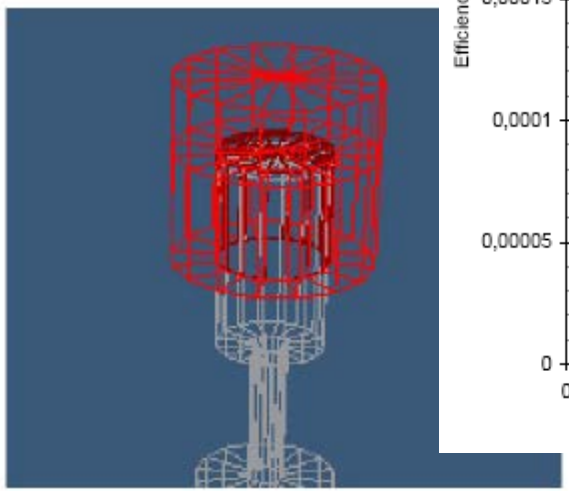
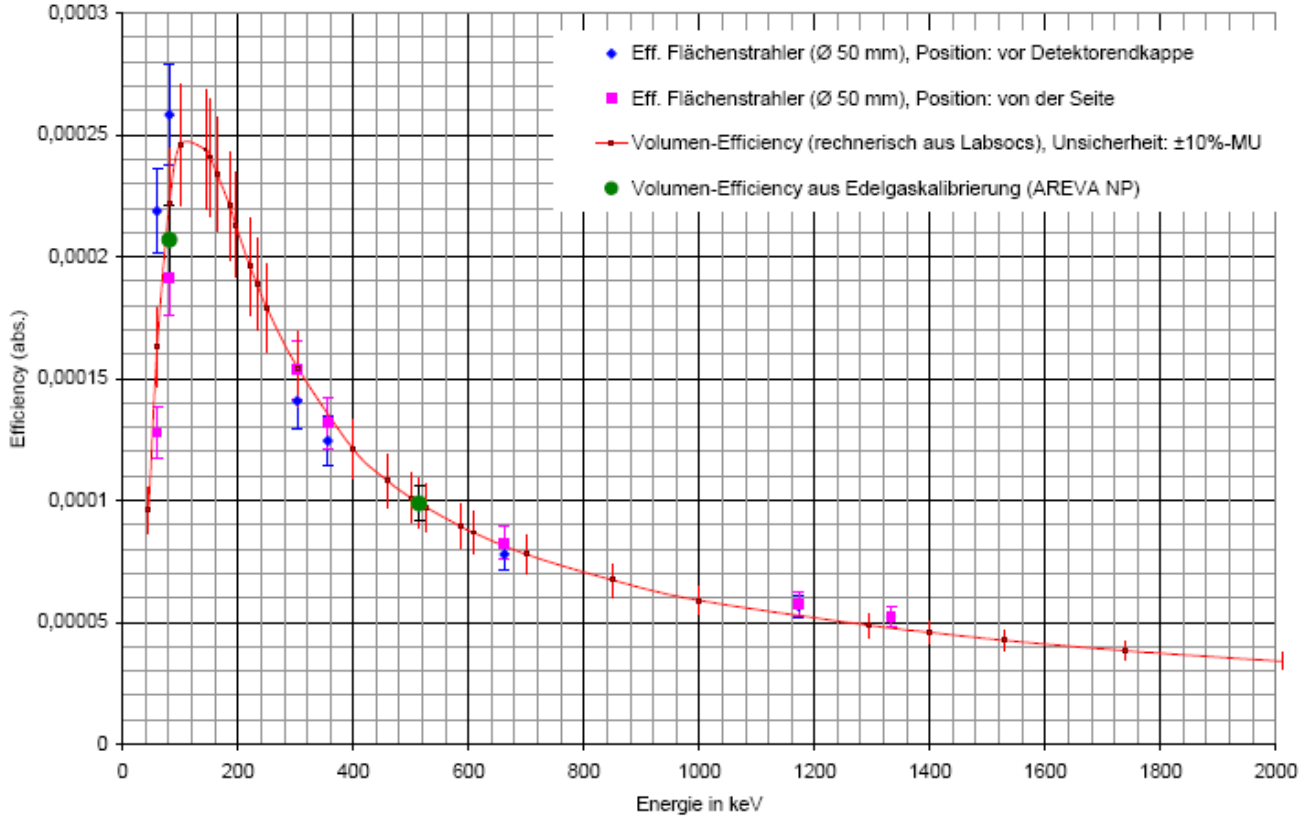
Spectroscopic noble gas monitor

- **Excellent agreement between verification measurements (green points) and ISOCS model (curve)**
  - **Xe-133 (0.93)**
  - **Kr-85 (0.99)**





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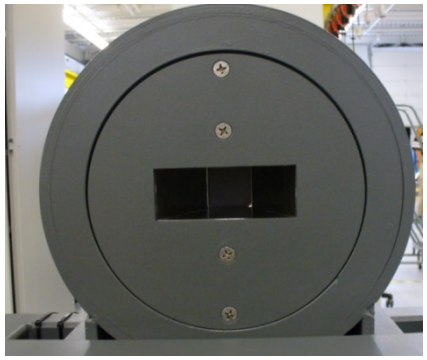
Gaseous Fission Product Monitor

- Collimated HPGe measurement of pipe
- Fuel integrity monitor
- GL1015 detector (1000 mm^2 x 1 mm)
  - planar detector with good sensitivity at low energies
  - also allows acquiring information from isotopes emitting higher energy gamma rays
  - uses a thin carbon composite window



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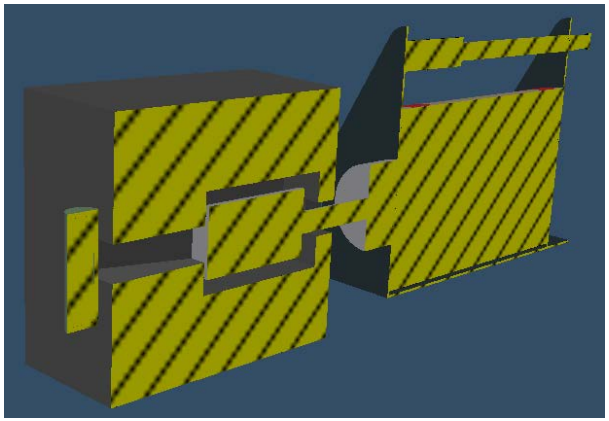
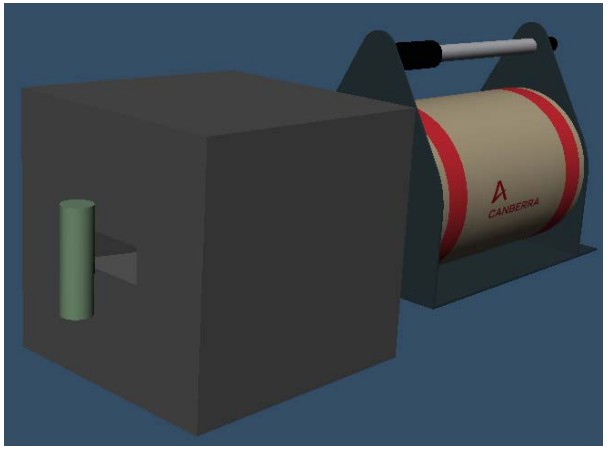
GFP system calibration

- **Fuel integrity monitor is calibrated using ISOCS software**
  - **The software generates absolute efficiencies for the measurement geometry**
- **Comparison of measurement/ISOCS:**
  - **59.5 keV -> 1.04**
  - **88.0 keV -> 1.04**
  - **122.1 keV -> 1.03**
  - **661.7 keV -> 1.04**





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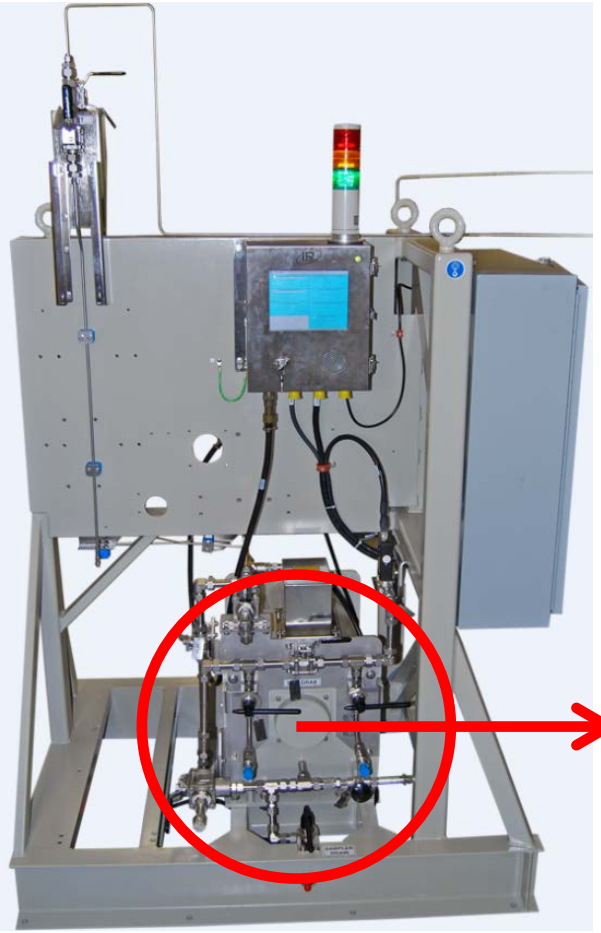
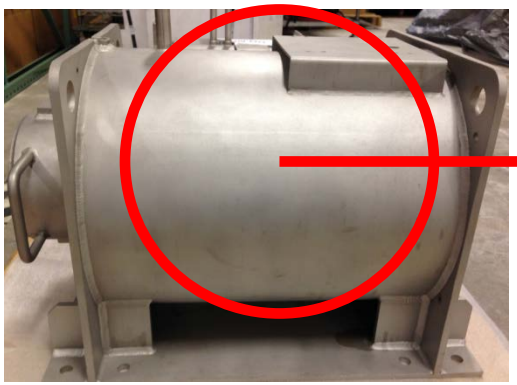
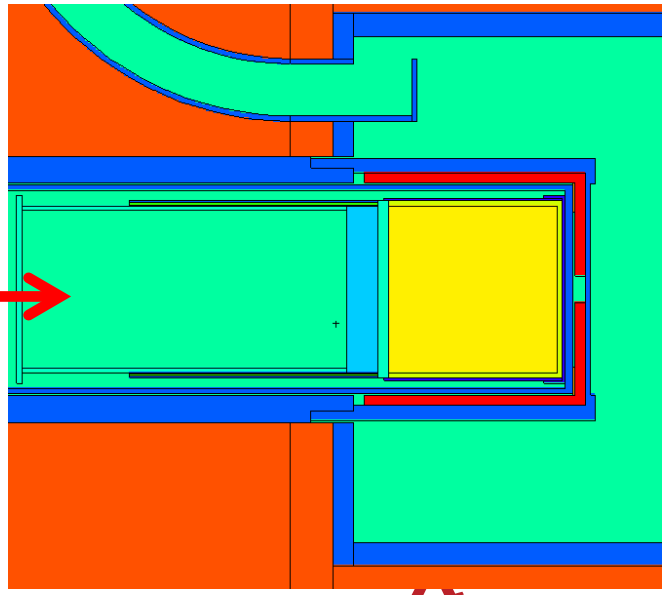
Extended range noble gas monitor

- 2x2 NaI with a special collimator to even the Kr-85 and Xe-133 response
- Modeled with MCNP
- Verified with Kr-85 measurement
- Measurement/MCNP ratio = 0.986
- Detector model also validated with point sources







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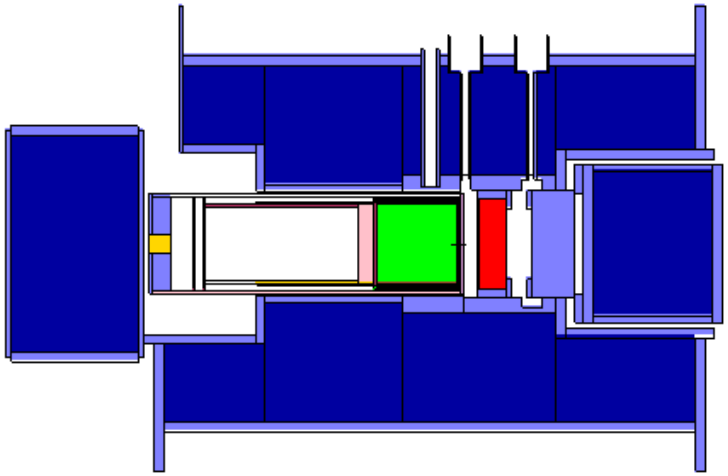
Portable Iodine/particulate monitor

- **Particulate channel – iCAM (calibrated with Cl-36 and Am-241)**
- **Iodine channel – calibrated with MCNP/measurement**
  - **Benchmark MCNP with Ba-133 – Agreement MCNP/Measured = 0.94**
  - **Extend to I-131 with MCNP**



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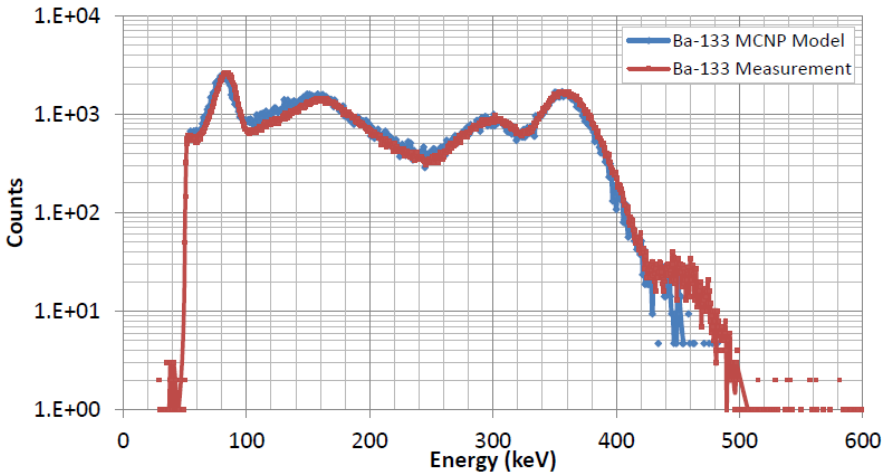
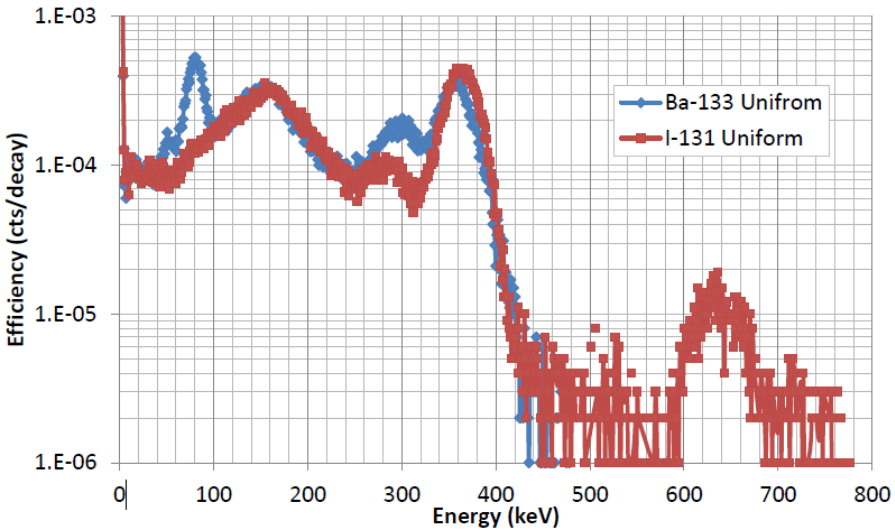
Portable Iodine/particulate monitor (continued)

- **Comparison of model to measurement**
  - **MCNP scaled by activity**
  - **Excellent agreement**
    - Shape
    - Magnitude



- **Extension to I-131**
  - **Both curves are MCNP**
  - **Extend to other isotopes**
  - **Extend to filter deposition**
    - Uniform
    - Surface
    - Exponential



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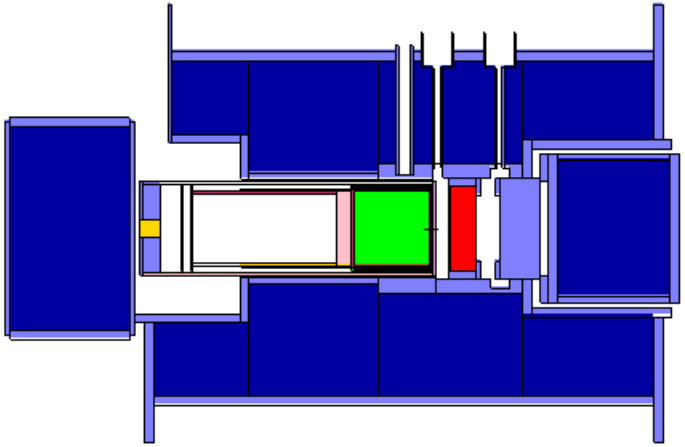
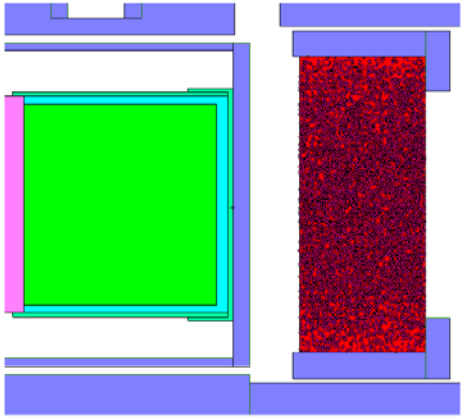
Portable Iodine/particulate monitor (continued)

- **Benchmark MCNP model with uniformly loaded and surface loaded sources**

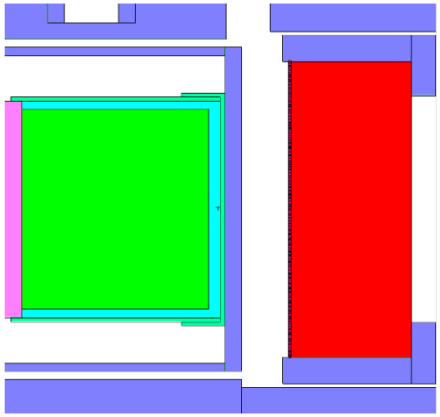


- **Extend to exponentially loaded with MCNP**

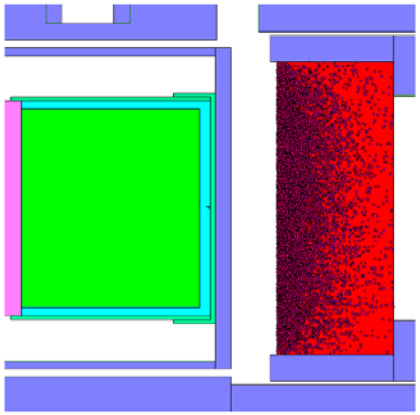
Uniform profile



Surface profile

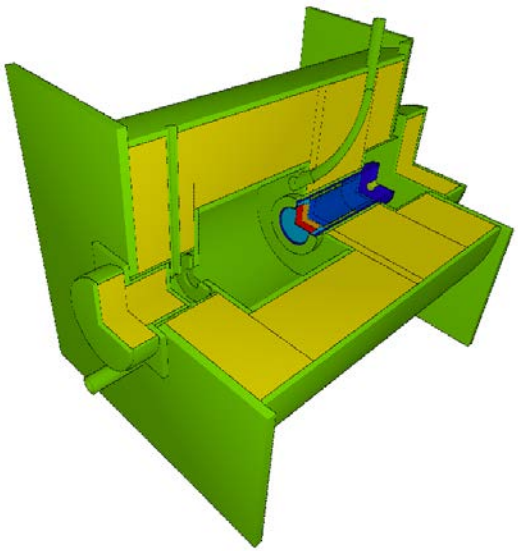


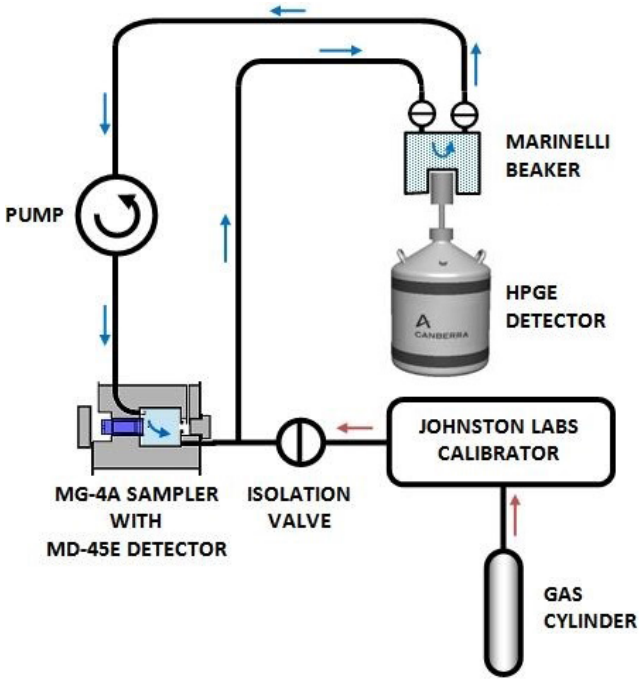
Exponential profile



Normal range noble gas monitor

- **Beta scintillator based noble gas measurement**
- **MCNP model benchmarked with Kr-85 measurement**
- **Activity concentration of calibration gas calculated by injection and measured with ISOCS characterized detector**





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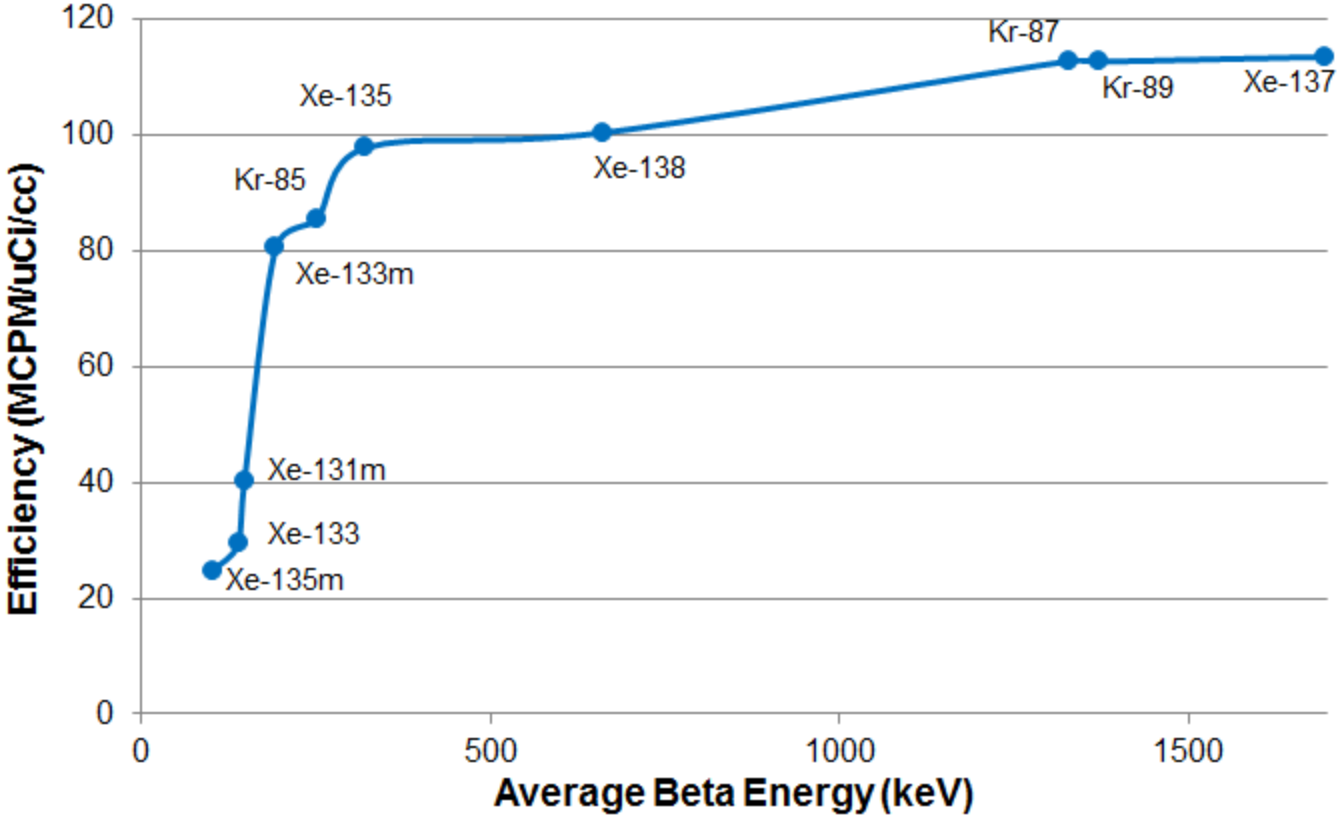
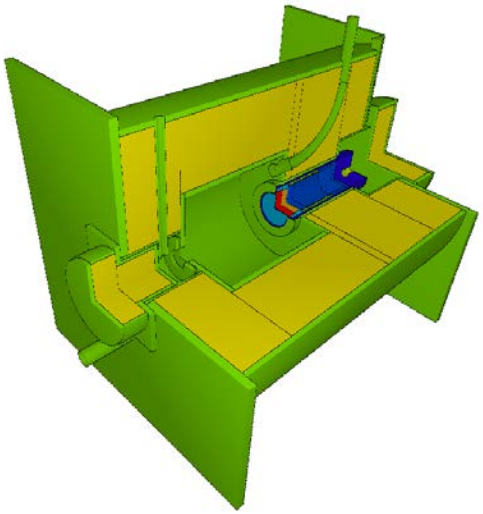
Normal range noble gas monitor (Continued)

- **Efficiencies for a number of nuclides generated with validated MCNP model**
- **Model also used to estimate the uncertainty in the primary calibration**





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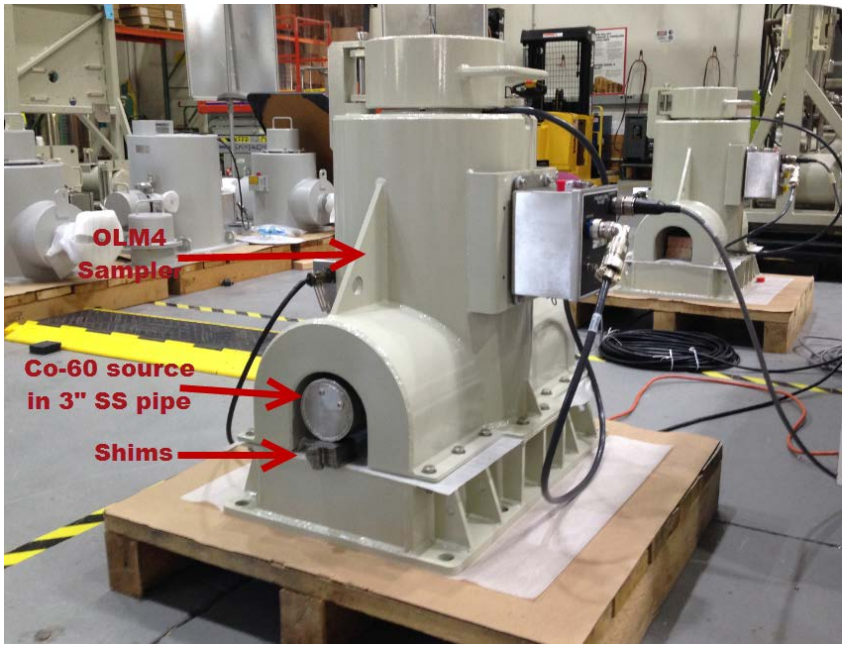
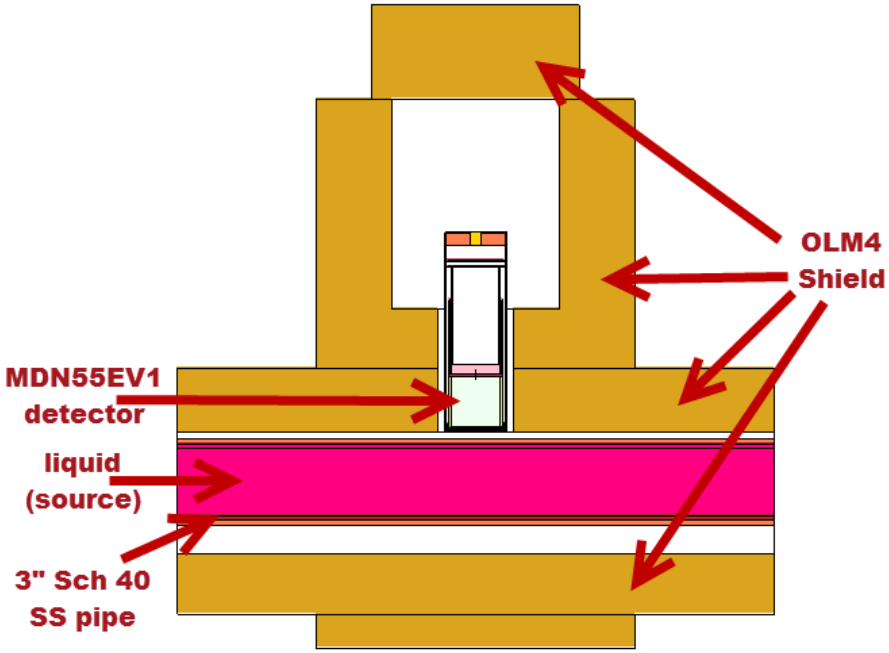
On-line monitor (OLM-4)

- **The installed pipe is a custom 3” schedule 40 SS pipe – lined with PTFE**
  - **Model and validate model with a standard 3” schedule 40 SS pipe filled with Co-60 matrix – agreement MCNP/Measured efficiency = 0.94**
  - **Extend MCNP model to PTFE lined pipe**
  - **Extend MCNP model to other nuclides**





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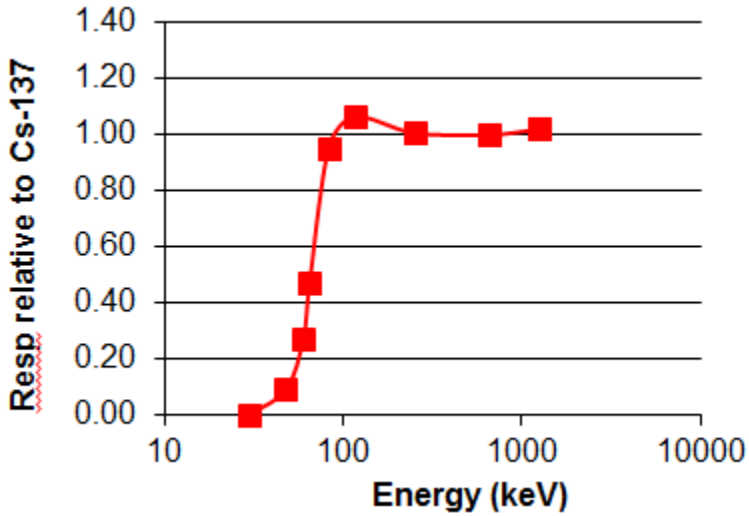
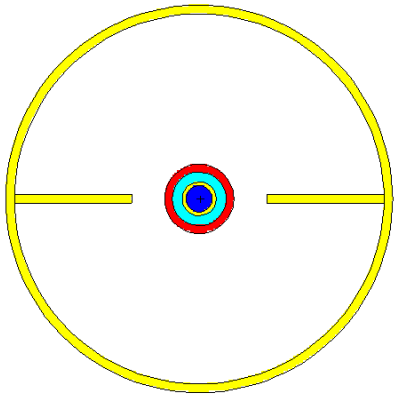
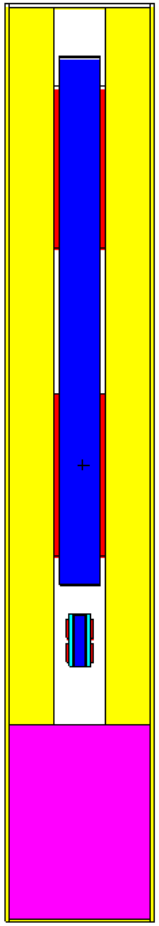
Environmental gamma monitor EcoGamma

- Model the response during prototype phase
- Validate model with simple measurements
- Confirm the probe would meet IEC 60532
  - Energy response
  - Variation with angle of incidence
- After MCNP model provides confidence, take prototypes to the lab







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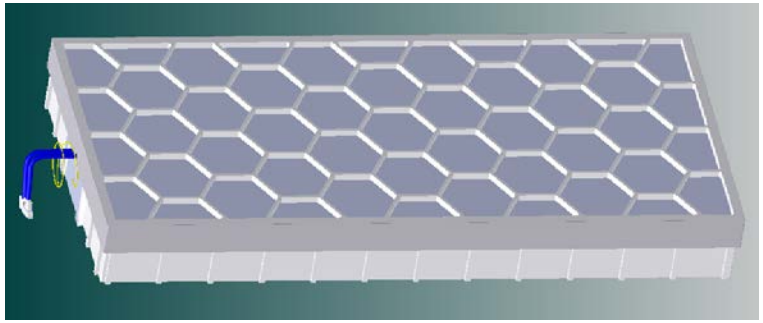
Sr-90 water monitor

- The response to the Fukushima NPP accident created extremely large volumes of radioactive water.
- Several water processing systems were built to process this water and remove various radionuclides.
- Development of a monitor to detect Sr-90 in water
  - Difficult because Sr-90 is a pure beta emitter
  - Other possible interference nuclides exist
- Cleanup goal is 0.15 Bq/L [4 pCi/L] for Sr-90.



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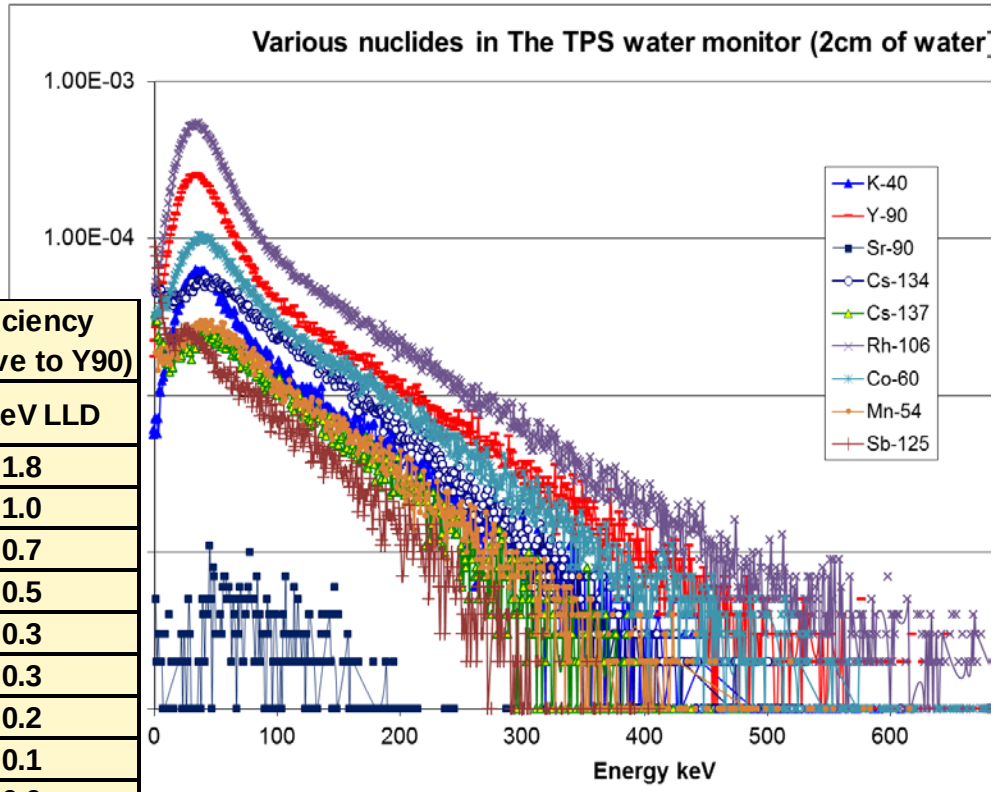
MCNP simulation used to predict the response of the detectors

- Very good for optimization – comparisons between various choices
- Efficiency prediction not as good as for gamma spectroscopy
  - Threshold not well known; Final design verified with sources
- Graphic below shows predicted response for nuclides in water
  - Includes gamma response into beta detector
  - All nuclides with = Bq/L
- This is Y-90 counter
  - Sr-90 response near zero
- Ru/Rh potential problem
  - High E betas
  - Many gammas
- Co-60 and Cs-134 also
  - Many gammas
- Separate gamma could give warning

Nuclide	Efficiency (relative to Y90)
	70 keV LLD
Rh-106	1.8
Y-90	1.0
Co-60	0.7
Cs-134	0.5
K-40	0.3
Mn-54	0.3
Cs-137	0.2
Sb-125	0.1
Sr-90	0.0
Ru-106	0.0



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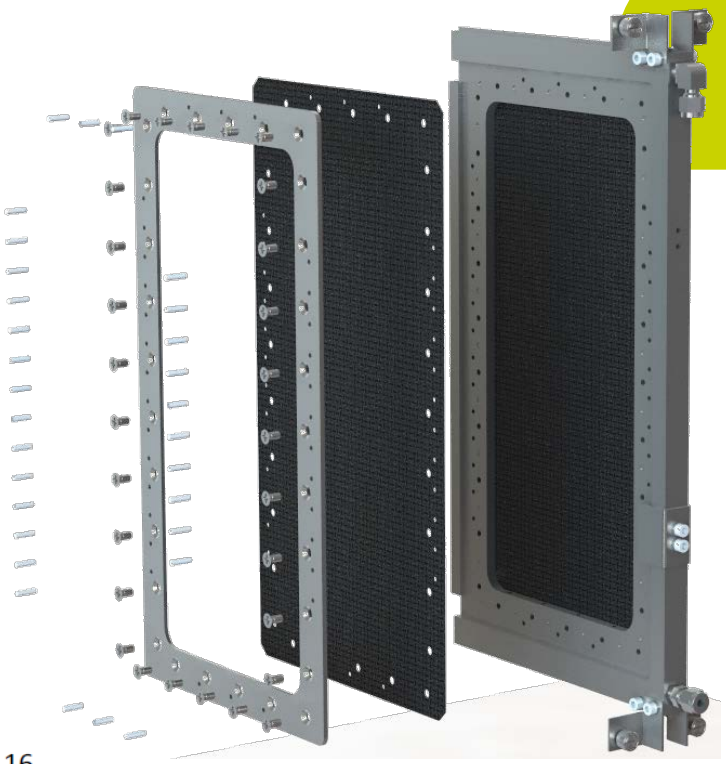
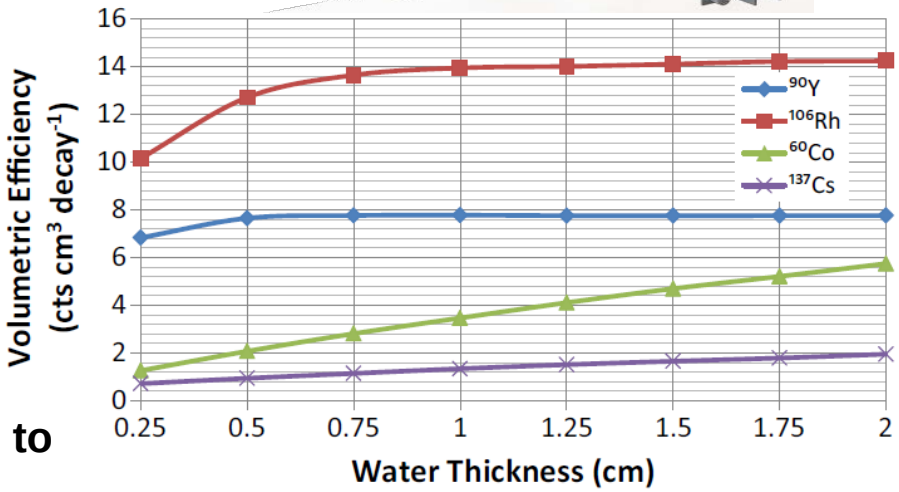
Water Chamber

- Size and thickness of water chamber optimized for Sr/Y-90 using MCNP simulations
- Y-90 - Max efficiency >0.5 cm
- Rh-106 - Max efficiency > 0.7 cm
- Co-60 and Cs-137
  - Efficiency drops as chamber gets smaller
  - Typical gamma response
- Optimum thickness was 5mm
- As-built was 7mm – mechanical limitations
- Carbon fiber window both sides
  - 0.5mm thick
  - Several pressure tested to destruction to prove they were strong enough





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Sr-90 water monitor Performance

- Calibrations performed with NIST-traceable Sr/Y-90 solution
- Efficiency ~44 cps per Bq/cm^3
- Background ~6 cps
- MDA: 18 Bq/L 10min; 7.5 Bq/L 60min; 3.3Bq/L 300min
  - 10CFR20 Table 2 release: 18 Bq/L = 50 mRem/yr for 100% intake all year
  - California EPA goal: 0.013 Bq/L
- Systems designed, produced, tested and delivered in 5-6 months
  - Faster than we quoted; Slower than customer wanted

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Conclusion

- **Mathematical models**
  - **MCNP – Monte Carlo**
  - **ISOCS – Rigorously validated MCNP model based on many measurements**
- **Mathematical efficiency used for:**
  - **Design phase of prototype systems**
  - **Uncertainty analysis**
  - **Nuclide/geometry extension**
  - **Calibration**
- **A number of examples:**
  - **Noble gas (spectroscopic and gross counting)**
  - **Liquid on-line and in-line monitors**
  - **Iodine monitors**
  - **Environmental gamma monitor**
  - **Sr-90 water monitor**

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Thank you!

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