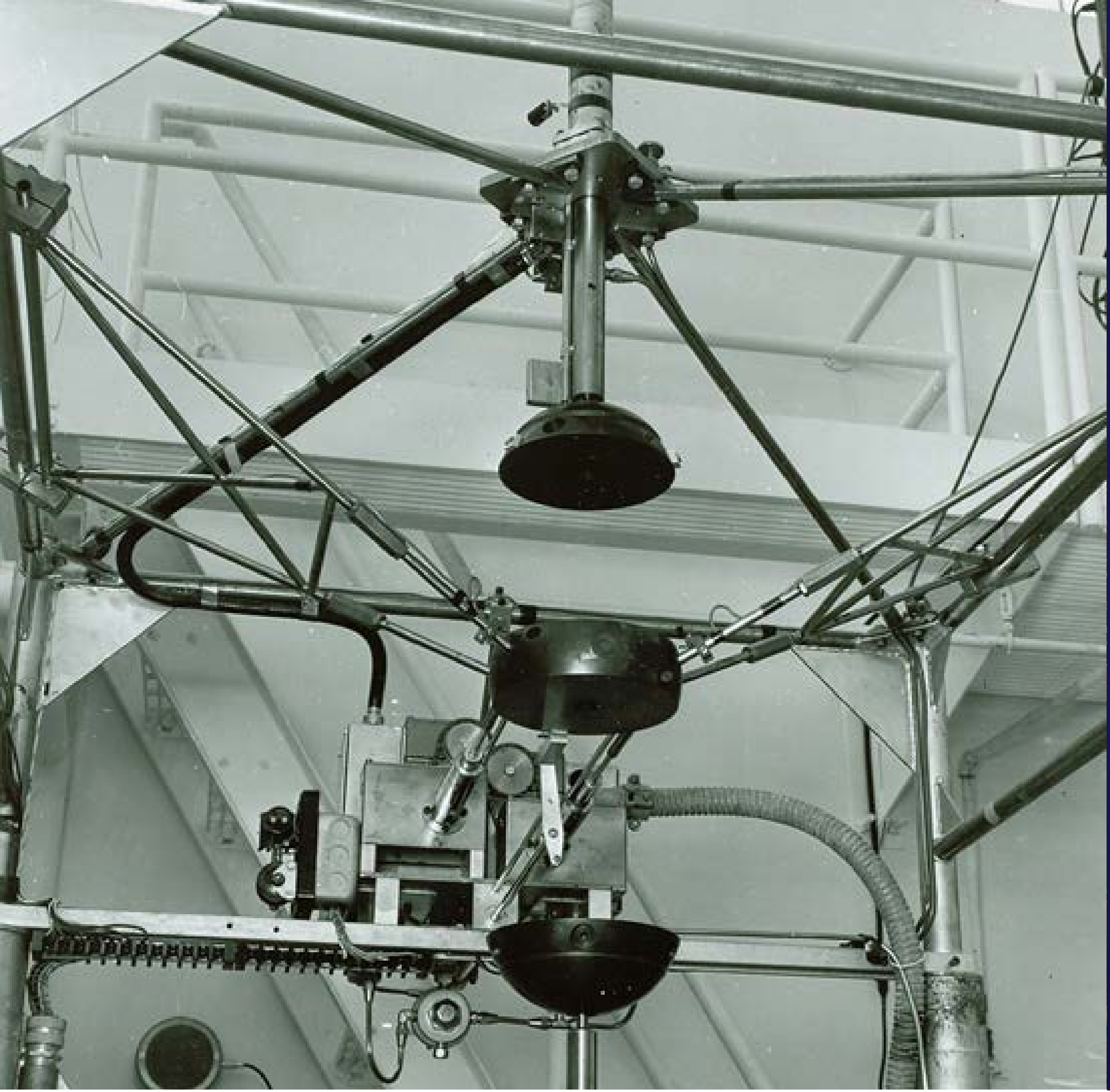

Los Alamos NATIONAL LABORATORY

EST. 1943

NNSA National Nuclear Security Administration

Development of a Research Reactor Protocol for Neutron Multiplication Measurements

R. Bahran[1], J. Hutchinson[1], J. Arthur[1,2], M. Smith-Nelson[1]
A. Sood[1], P. Caracappa[3], N. Thompson[3], S. Pozzi[2]

[1]Los Alamos National Laboratory

[2]University of Michigan

[3]Rensselaer Polytechnic Institute

LA-UR-16-28556

Introduction

BACKGROUND

Early Acknowledgements

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- **Neutron Multiplication Measurements at a Research Reactor – Years in the Making**
    - 1980s - 2000s: Major Progress in Subcritical Neutron Multiplication Measurements/Simulations

      See recent paper by J. Hutchinson et al. “Subcritical Multiplication Experiments & Simulations: Overview and Recent Advances” Proceedings of ANTPC 2016, Santa Fe, NM

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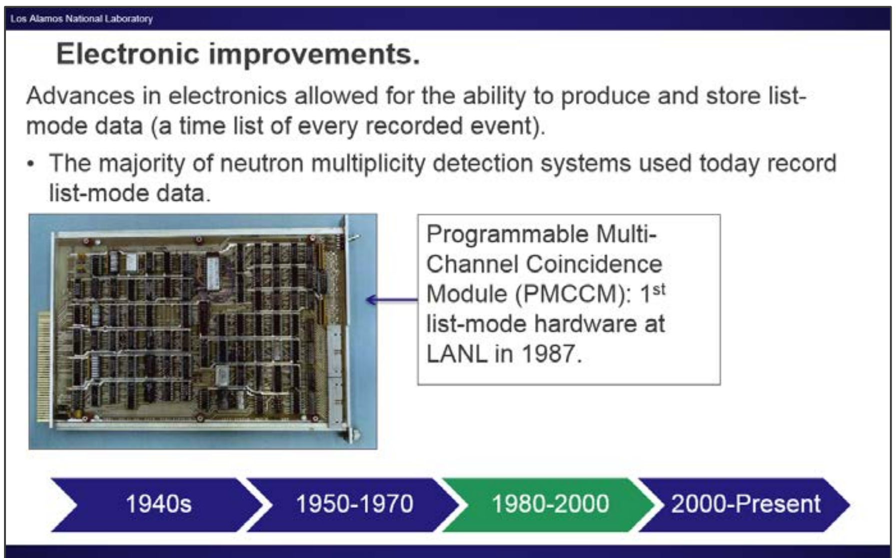

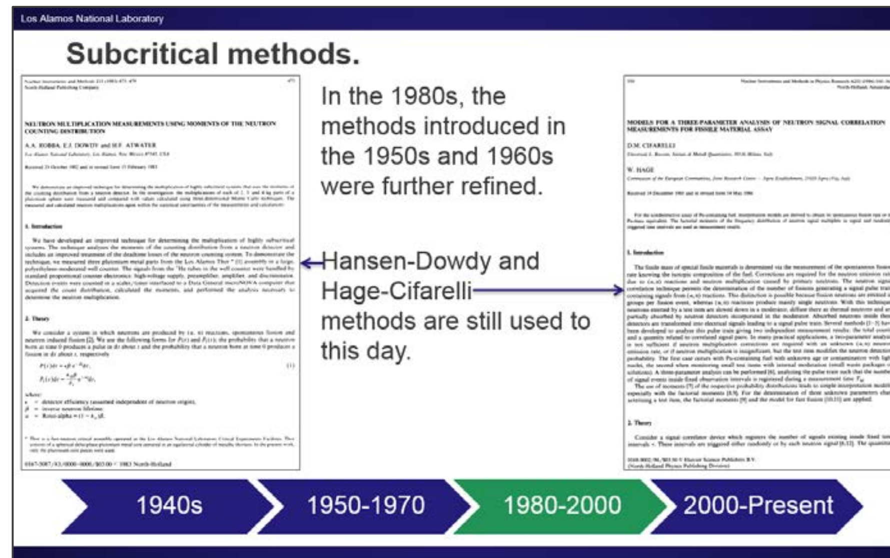

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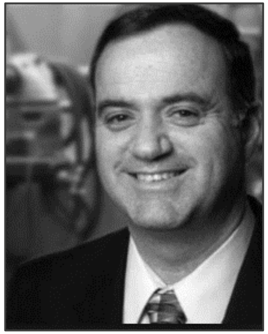

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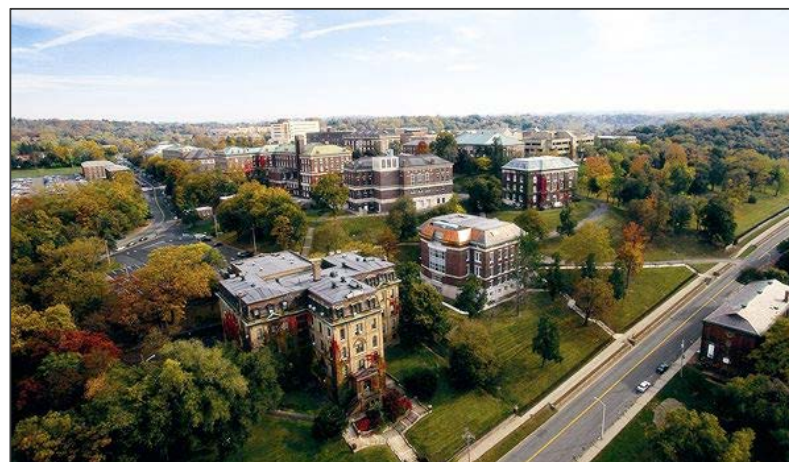

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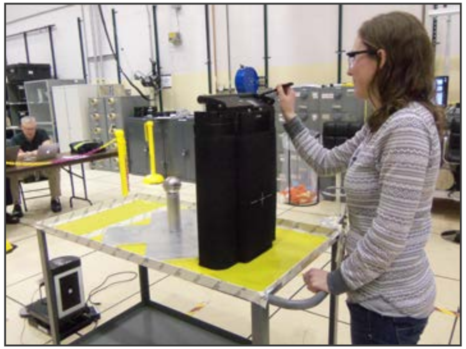

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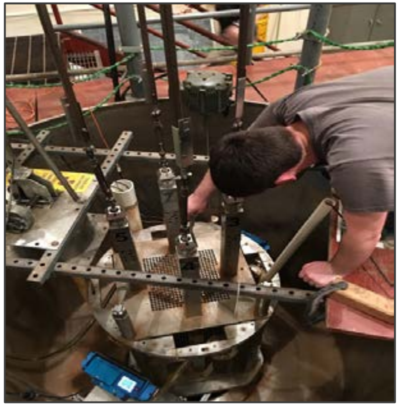


  - 2016: Execute first series of measurements at RPI Reactor Critical Facility

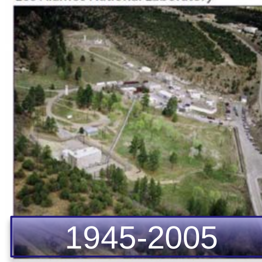
Motivation

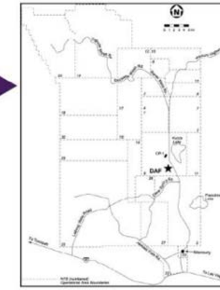
LANL National Criticality Experiment Research Center

- **Mission**
  - o Conduct experiments on critical assemblies with fissile material at or near criticality in order to explore reactivity phenomena, and to operate the assemblies in the regions from subcritical through delayed critical.

- **Facility/Capabilities**
  - o Cat I Special Nuclear Material
  - o Subject Matter Expertise
    - Critical experiments: Planet, Comet, Godiva IV, and Flat-Top
    - Subcritical Experiments and Radiation Test Object operations

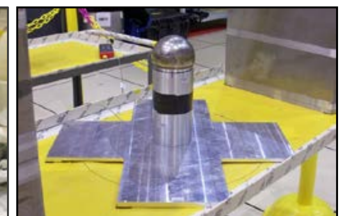
TA-18, Pajarito Site
Los Alamos National Laboratory





Device Assembly Facility (DAF)
Nevada Test Site (NTS)

September 2004	December 2004	September 2005	October 2005
First shipment from LANL TA-18 to the DAF	First security category 1 shipment from LANL to the DAF	New start of hazard category 2 operations approved	Final shipment to reduce TA-18 to below security category 2

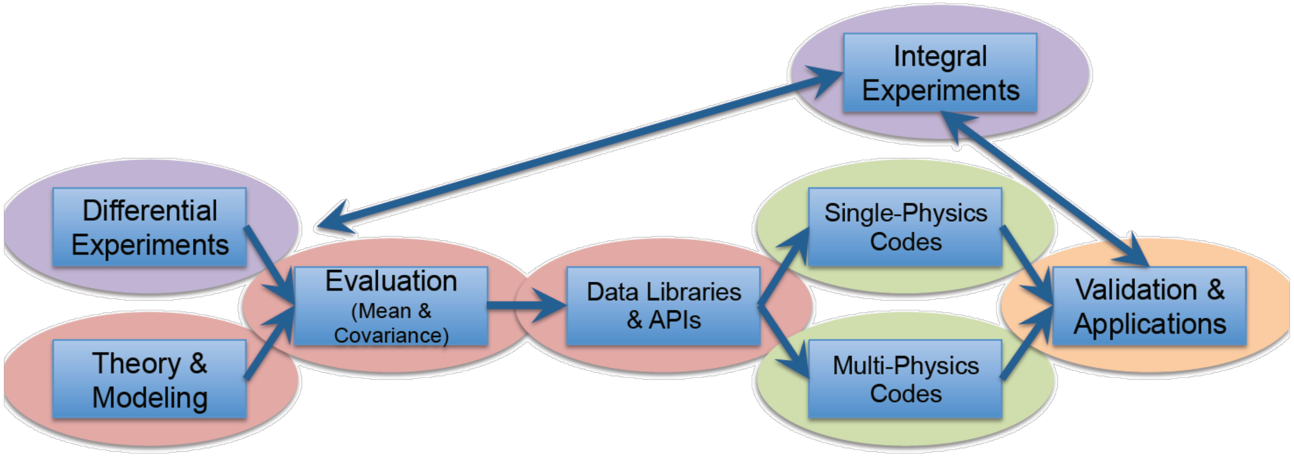


4 Critical Assemblies and Lots and Lots of Special Nuclear Material

Nuclear Data Validation

Predictive Radiation Transport Simulation Pipeline: Comprehensive, Complex, and (reasonably) Coordinated

Figure adopted from Morgan White (LANL)



Cross-section and emission measurements

Heuristic and advanced theory development

Expert judgment and evaluation tools

ENDF/B libraries
-neutron
-gamma (photons)
-charged particles
-decays

Nuclear data processing

Nuclear data libraries
-neutron/photon
-charged particles
-thermonuclear rx
-radchem

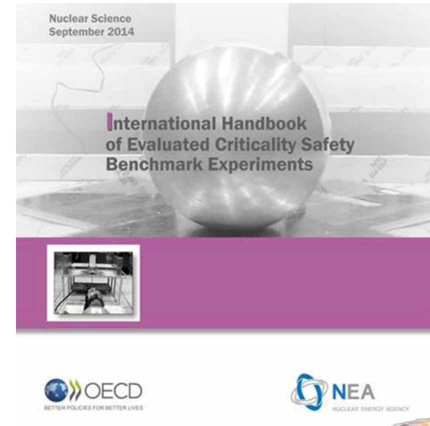
Standardized interfaces

Integral data

Single-physics
- critical assemblies
- pulsed spheres
Multi-physics
- NTS data

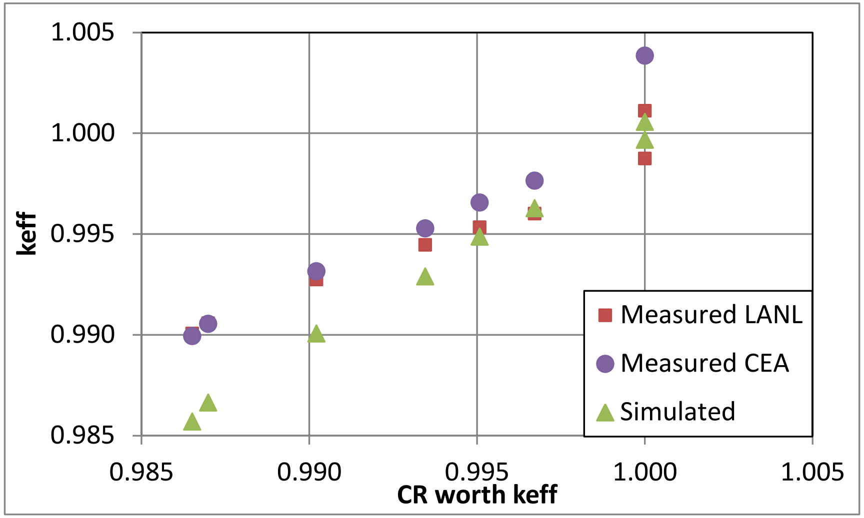
Recent Advances in Subcritical Experiments

- **We have come a long way since the first subcritical measurements at CP-1 in 1942.**
- **Many organizations (LANL, LLNL, SNL, IAEA, IRSN, CEA, AWE, universities, and others) have pursued subcritical experiments and/or simulations in recent years.**
- **The BeRP ball reflected by nickel benchmark evaluation was published in the 2014 edition of the ICSBEP handbook.**
- **This benchmark was the first:**
  - Published benchmark evaluation of measurements performed at DAF.
  - Benchmark evaluation using new MCNP capabilities for subcritical systems (the MCNP list-mode patch and MCNP6 list-mode capabilities).
  - Benchmark using the Feynman Variance-to-Mean method.
  - LANL-led subcritical experiment in the ICSBEP handbook.
- **This benchmark was the culmination of several years of subcritical experiment research.**
- **Additional benchmark (BeRP-tungsten) completed, and BeRP-copper (SCRaP) to be executed this year.**



Recent measurements at very high multiplication

| at and near delayed critical |



Comparison of keff measured by multiplicity analysis versus control rod worth on Godiva IV.

Thesis of Amaury Chapelle, CEA included measurements on Caliban, Godiva IV, Planet, and Flat-Top.

Université de Caen Basse-Normandie

Ecole doctorale *SIMEM – Sciences des Structures, de l'Information, de la Matière Et des Matériaux*

Thèse de doctorat

présentée et soutenue le : *12/05/2014*

par

Amaury Chapelle

pour obtenir le

Doctorat de l'Université de Caen Basse-Normandie

Spécialité : *TH211, Constituants élémentaires et physique théorique*

Mesures de bruit neutronique auprès des réacteurs
Caliban, Godiva IV, Planet et Flattop
Détermination des paramètres cinétiques et des incertitudes associées

Directeur de thèse : *Professeur Gilles Ban*

Jury

Paul Reuss, professeur INSTN (rapporteur)
Pablo Rubiolo, professeur des universités, PHELMA Grenoble (rapporteur)
Hugues Delorme, enseignant de neutronique / maître de conférence, Ecole des Applications Militaires de l'Energie Atomique (EAMEA)
Pierre Casoli, Ingénieur chercheur, CEA, centre de Valduc
Nicolas Authier, Ingénieur chercheur, CEA, centre de Valduc
Gilles Ban, professeur des universités, ENSICAEN (directeur de thèse)

Jury invité :

Jesson Hutchinson, chercheur, Los Alamos National Laboratory
Capitaine de vaisseau Frédéric Janci, commandant l'Ecole des Applications Militaires de l'Energie Atomique (EAMEA)

Goal

- **Expand upon previous LANL benchmark-quality subcritical experiments**
  - Next step in advanced subcritical neutron measurements: establishing research reactor measurement protocol
  - Benchmark-quality integral measurements at different known reactivity states
- **Spatial complexity, different materials (fuel, moderator), and system-specific neutron cross-section sensitivities (various energy ranges and reactions)**

Reactor Critical Facility

BACKGROUND

RCF core

- **Located at Rensselaer Polytechnic Institute**
- **0-power reactor with negligible burn-up**
- **LEU SPERT-type F-1 fuel pins**
  - Enrichment of 4.82% U-235 by weight
- **Stainless steel cladding and B-impregnated Fe rods**
- **Water moderated**

RCF facility

Correlated neutron detection

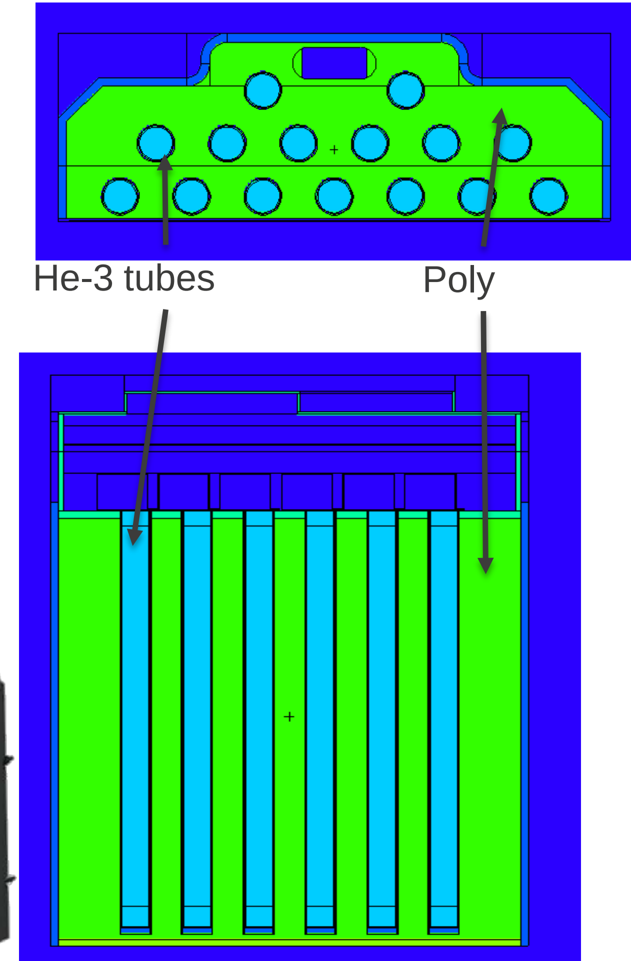
BACKGROUND

MC-15

- **15 He-3 tubes in poly**
- **Removable cadmium shield**
- **Time of arrival of pulse and detector of interaction are recorded**
  - List-mode data

Table III. ^{3}He tube information	
Manufacturer	Reuter-Stokes
Model Number	RS-P4-0815-103
Body Material	Aluminum 1100
External Diameter	1.00 inch
Thickness	1/32 inch
Height (including cladding)	41.6 cm
^{3}He Pressure	150 psia
Active Length	15.0 inch

MC15 model – top view



MC15 model – side view

Data processing

- **Feynman histogram: list-mode data binned into multiplets according to specified time widths (Momentum)**
- **Singles rate (R1): frequency of detection of single neutrons**
- **Doubles rate (R2): frequency of detection of two neutrons from the same fission chain**

$$R1 = \frac{m_1(\tau)}{\tau} \qquad \textbf{(1)}$$

$$R2 = \frac{Y_2(\tau)}{\omega_2(\lambda,\tau)} \qquad \textbf{(2)}$$

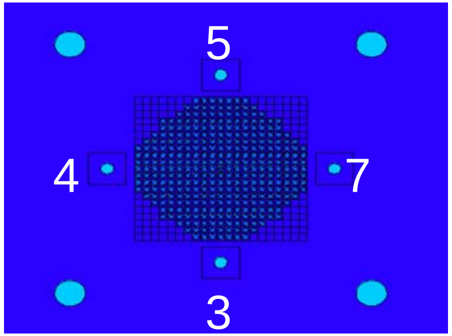
$$Y_2(\tau) = \frac{m_2(\tau)-\frac{1}{2}[m_1(\tau)]^2}{\tau} \qquad \textbf{(3)}$$

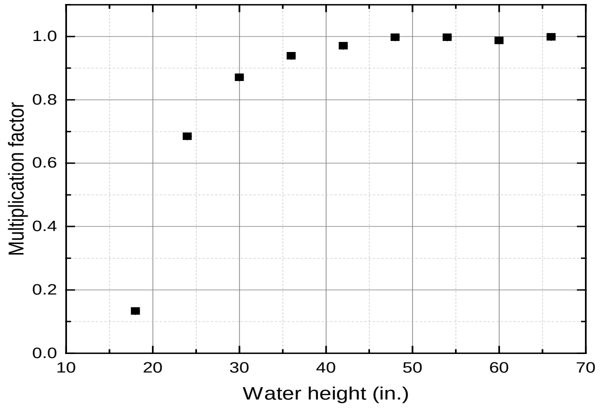
$$\omega_2(\lambda,\tau) = 1 - \frac{1-e^{-\lambda\tau}}{\lambda\tau} \qquad \textbf{(4)}$$

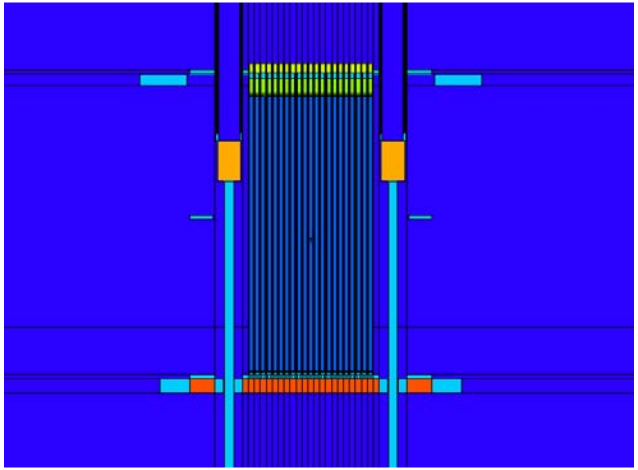
Simulations

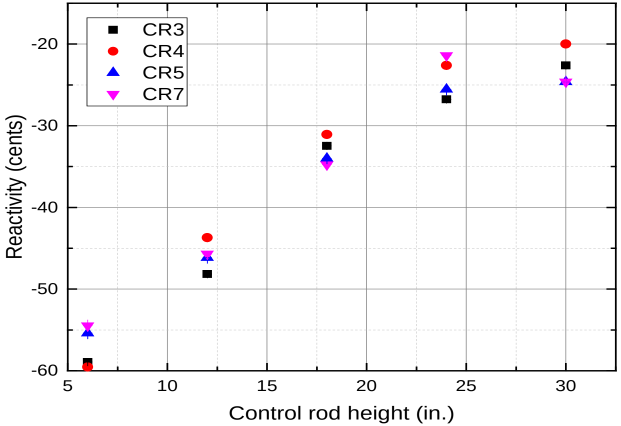
METHODS

MCNP model (RCF)

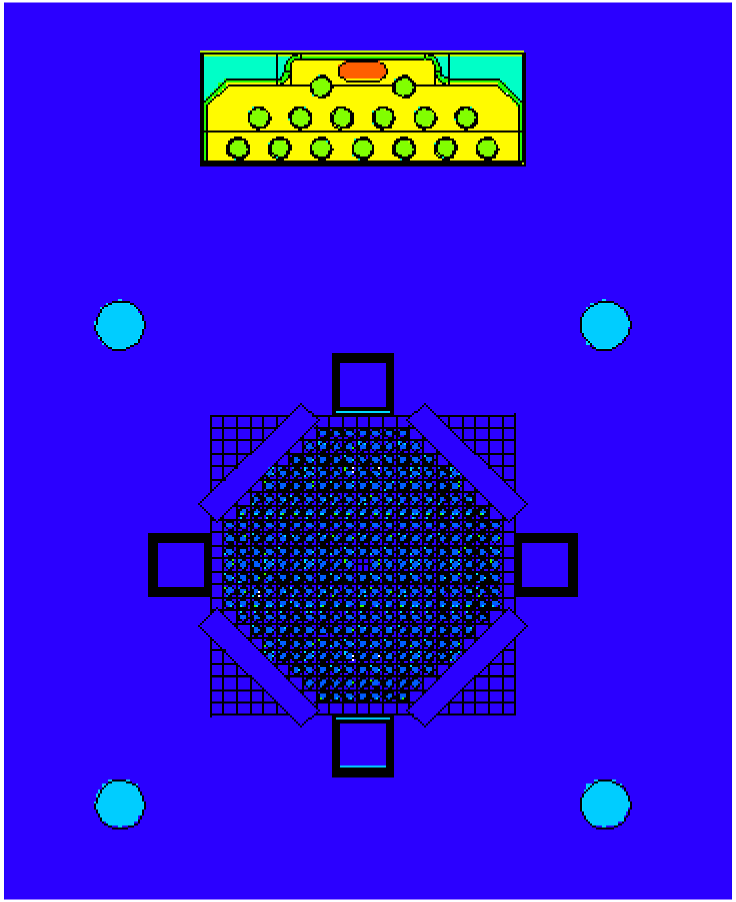


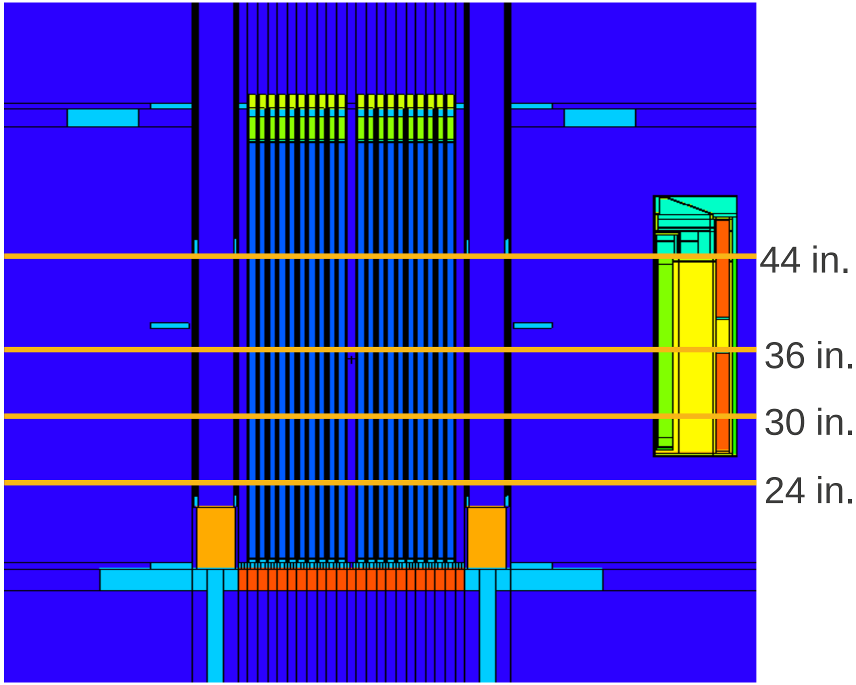






MCNP model (RCF and MC15)



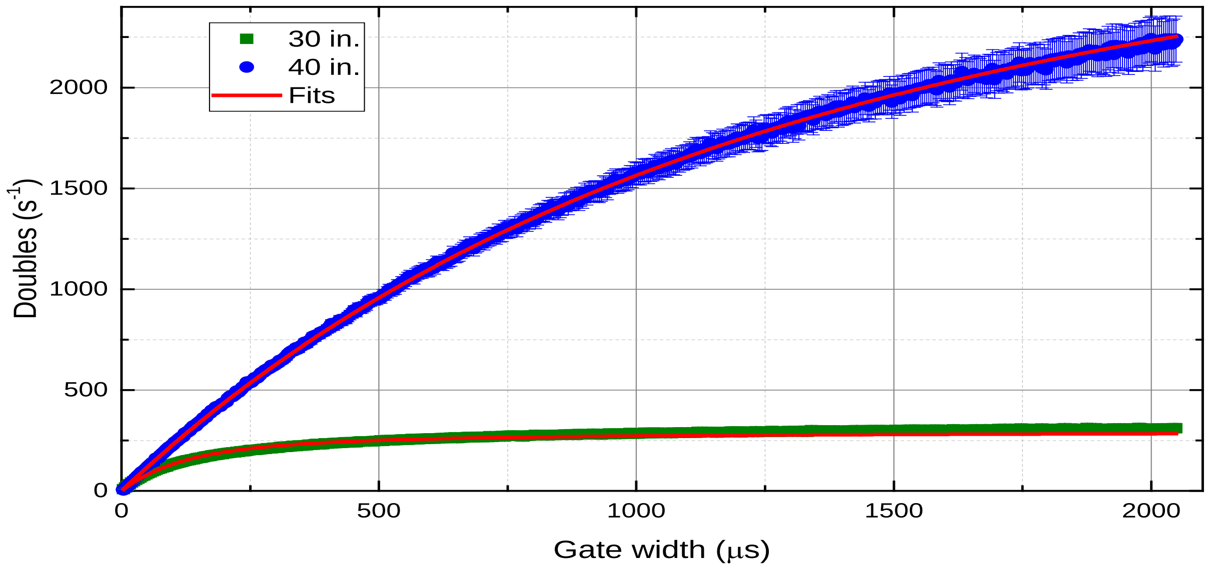


Measurement Configuration Optimization

- **Optimized parameters:**
  - 10^3-10^5 s^{-1} singles rate
  - Good fit (quantified by χ^2) of doubles rate vs. gate width
- **Possible source positions**
  - **Center**: at axial centerline of fuel and in center of core
  - **Opposite**: at axial centerline of fuel and on opposite side of core from MC15
  - **Opposite offset**: near the bottom of the fuel pins and on opposite side of core from MC15

Detector distance (in.)	Source strength (n/s)	Source position	Water height (in.)	Singles rate (s^{-1})	Doubles rate (s^{-1})	χ^2
13.8 (35 cm)	**10^5**	**center**	**36**	**2733±6**	**545±44**	**0.293**
19.7 (50 cm)	10^5	center	36	1098±4	60±11	0.310
13.8	10^6	center	36	26693±62	5061±3576	0.662
13.8	10^7	center	36	247560±28	Unable to determine	65.12
13.8	10^5	opposite	36	687±3	175±12	0.202
13.8	10^5	opposite offset	36	658±2	304±8	0.207

Measurement Configuration Optimization



Detector distance (in.)	Source strength (n/s)	Source position	Water height (in.)	Singles rate (s^{-1})	Doubles rate (s^{-1})	χ^2
13.8 (35 cm)	125210	center	18	3026±1	130±5	0.384
13.8	125210	center	30	3866±2	316±13	0.384
13.8	125210	center	36	3448±3	704±27	0.379

Experiment

METHODS

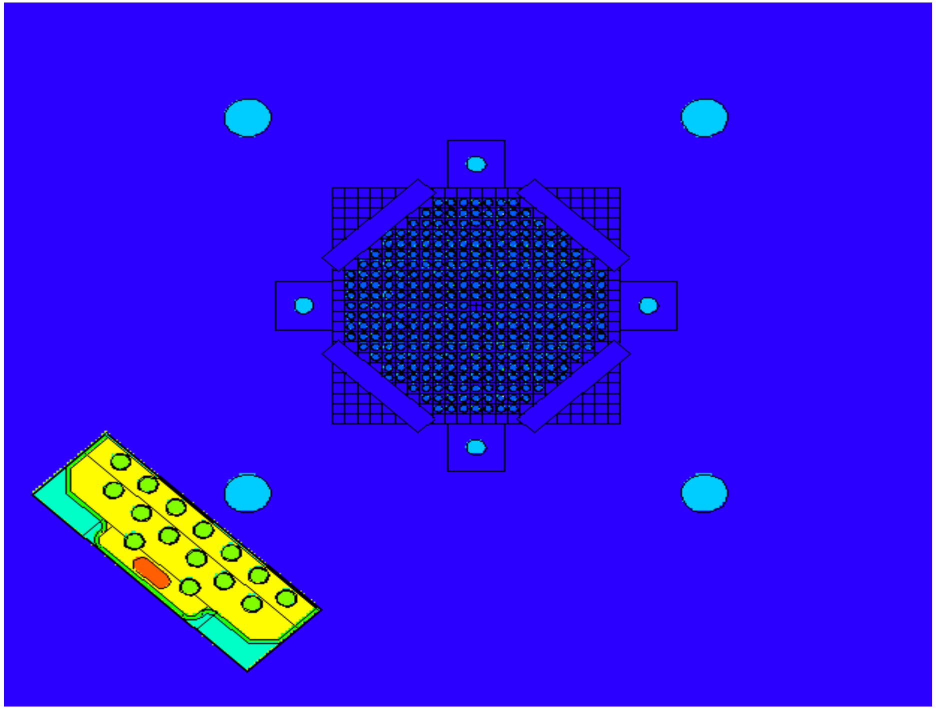
Planned configurations

- **MC15 13.8 in. (35 cm) from center of core, with vertical midpoint of active region at same height as axial midpoint of fuel rods**

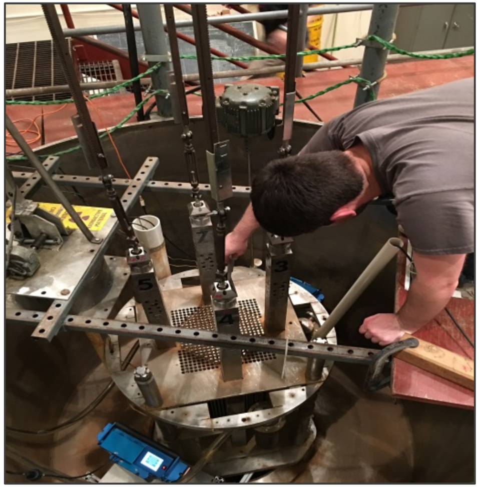
Water height (in.)	Fuel loading	Cf-252 source	MC15 detector
18	333 fuel pins, center pin absent	Replacing center fuel pin	13.8 in. (35 cm) from center of core
30	333 fuel pins, center pin absent	Replacing center fuel pin	13.8 in. from center of core
36	333 fuel pins, center pin absent	Replacing center fuel pin	13.8 in. from center of core
44	333 fuel pins, center pin absent	Replacing center fuel pin	13.8 in. from center of core
Variable	0 fuel pins	Replacing center fuel pin	13.8 in. from center of core

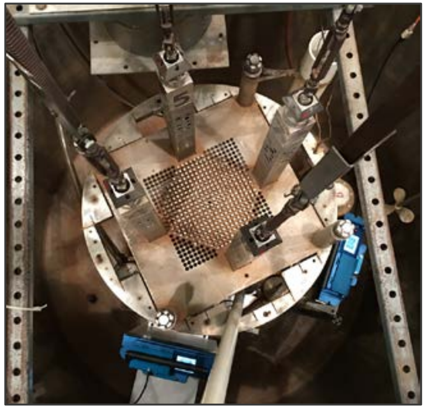
New geometry

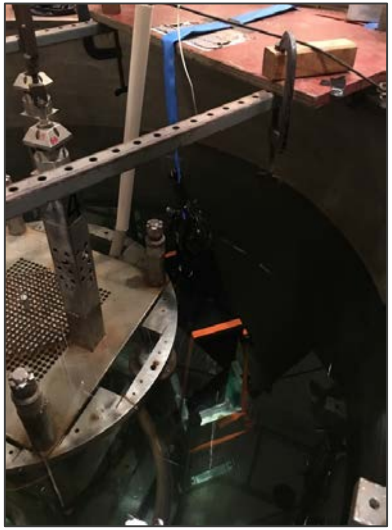
- **Only detector position changes (19.1 in. / 48.5 cm distance)**



Experiment







Completed configurations

Configuration #	Water height	CR3 height	CR4 height	CR5 height	CR7 height	Intended reactivity
1	44 in.	36 in.	36 in.	36 in.	36 in.	-
2	36 in.	36 in.	36 in.	36 in.	36 in.	-
3	30 in.	36 in.	36 in.	36 in.	36 in.	-
4	24 in.	36 in.	36 in.	36 in.	36 in.	-
5	67 in.	0 in.	0 in.	0 in.	0 in.	-
6	67 in.	20 in.	20 in.	20 in.	20 in.	-$0.50
7	67 in.	16 in.	16 in.	16 in.	16 in.	-$1.00
8	67 in.	25 in.	25 in.	25 in.	25 in.	Delayed critical
9	67 in.	36 in.	36 in.	21 in.	21 in.	Delayed critical

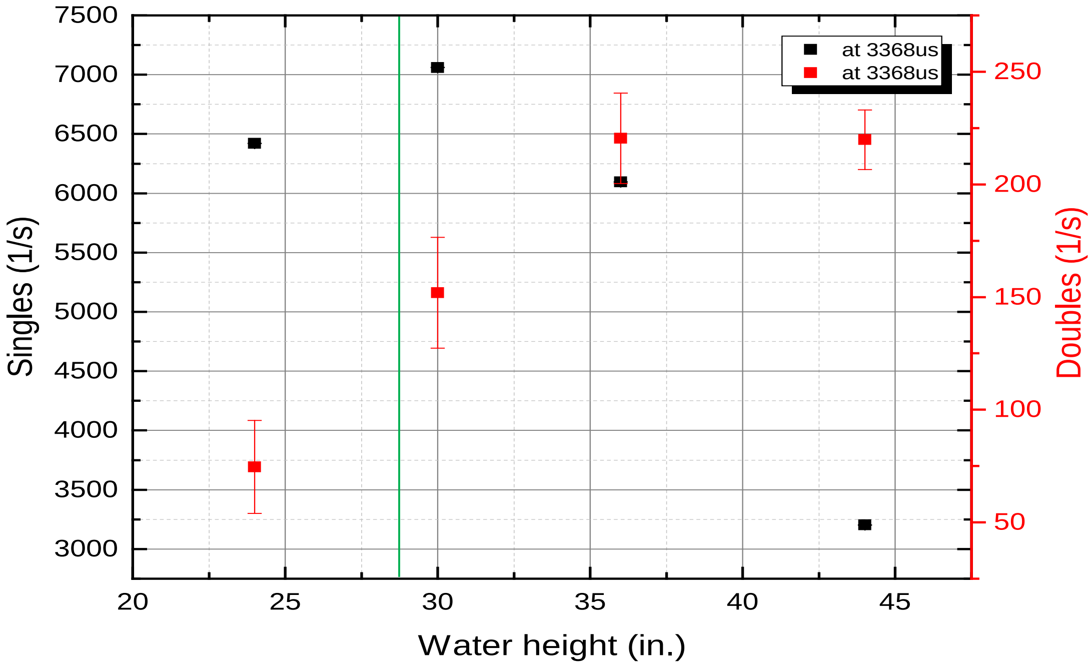
Control rods completely withdrawn: 36 in.
Control rods completely inserted: 0 in.

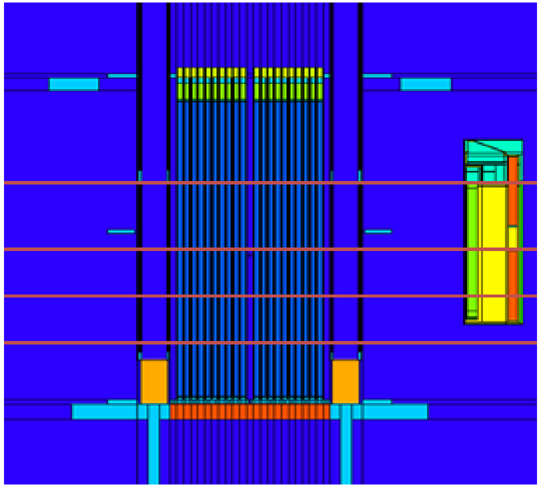
Cf-252 source with strength of 125210 n/sec during measurements.

Simulations vs. Experiment

PRELIMINARY RESULTS

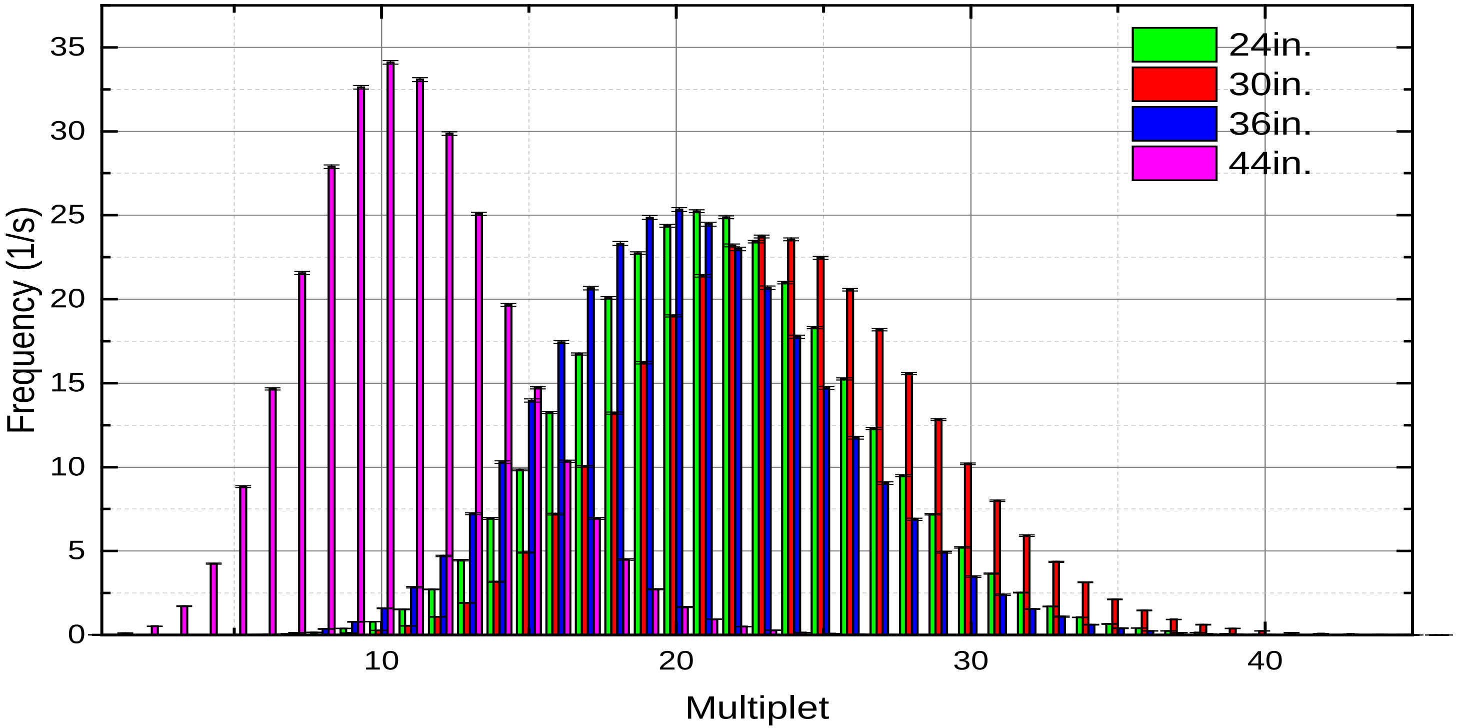
Singles/doubles vs water height



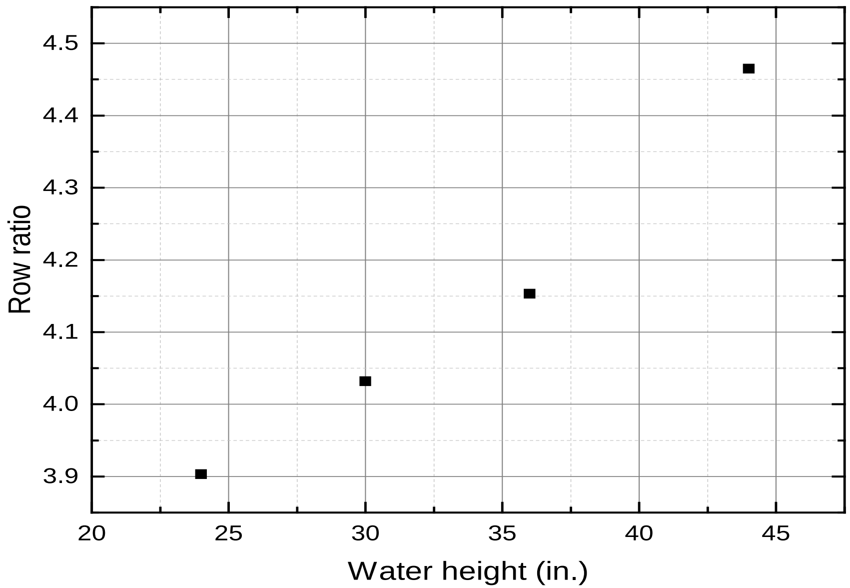


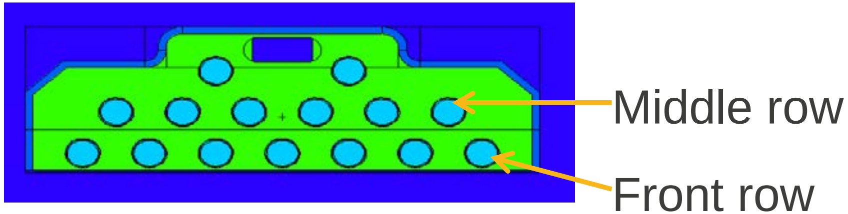
Note: All of the following results were obtained at a gate width of 3368 μs

Feynman histograms

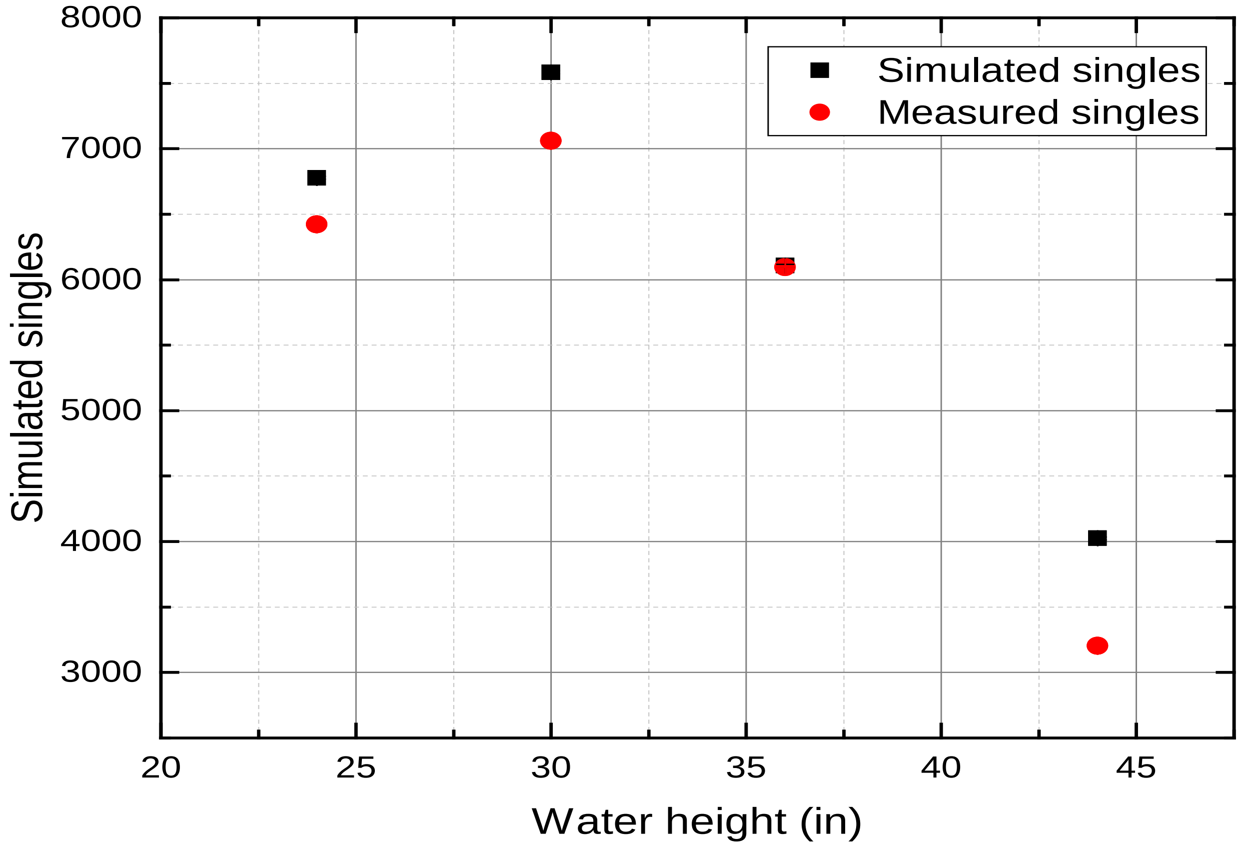


MC15 row ratio vs water height





Measured vs simulated



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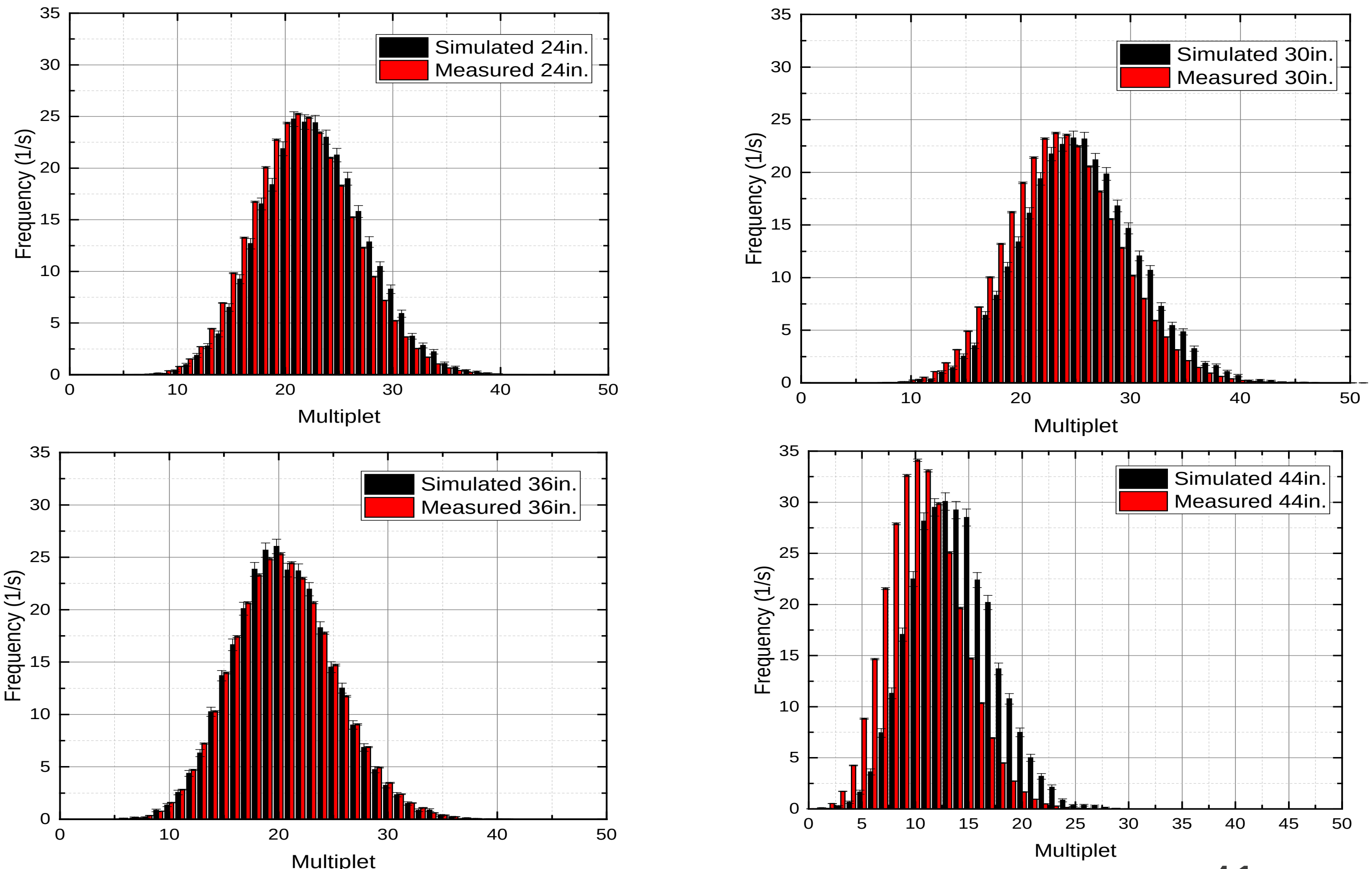
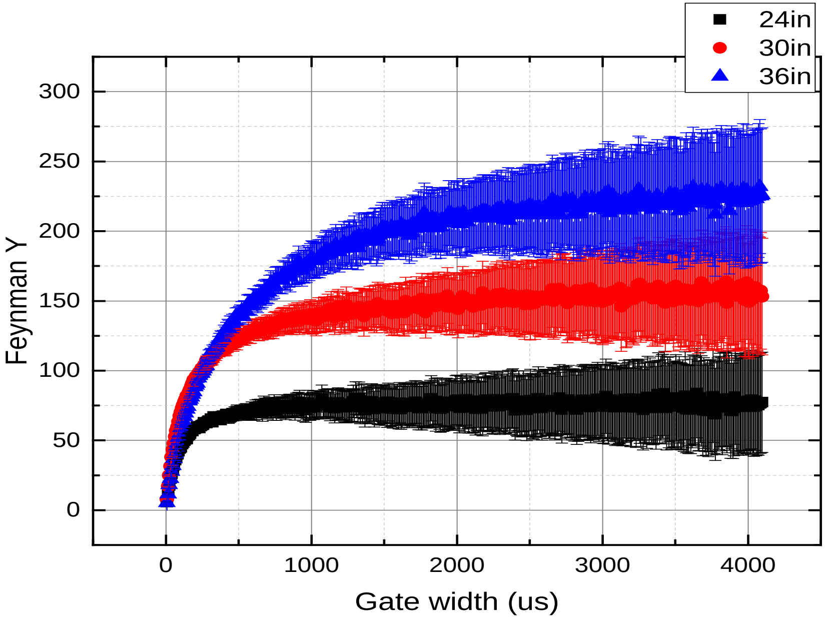
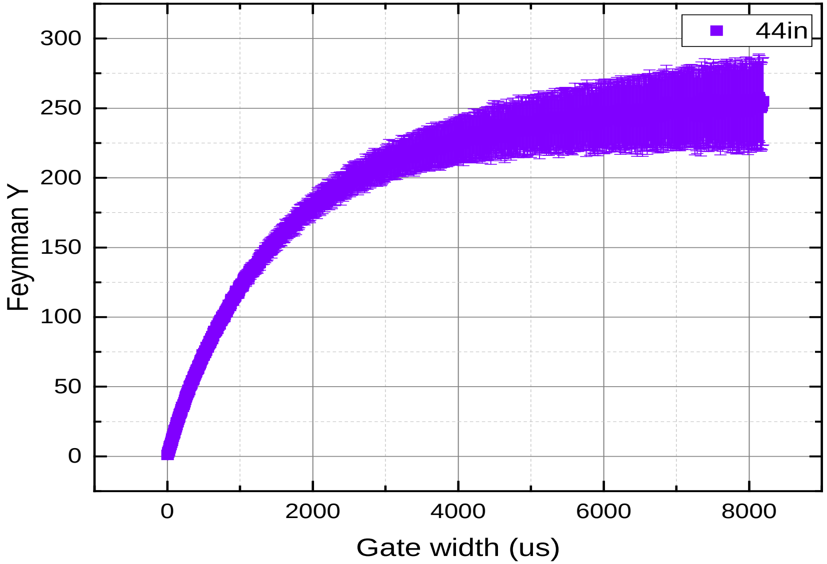


Feynman Y vs gate width





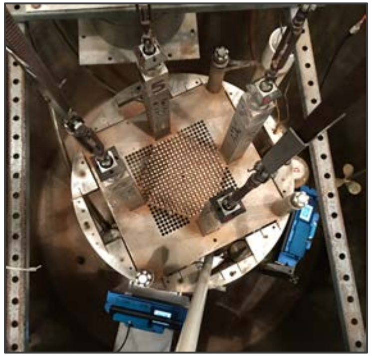
Next Steps

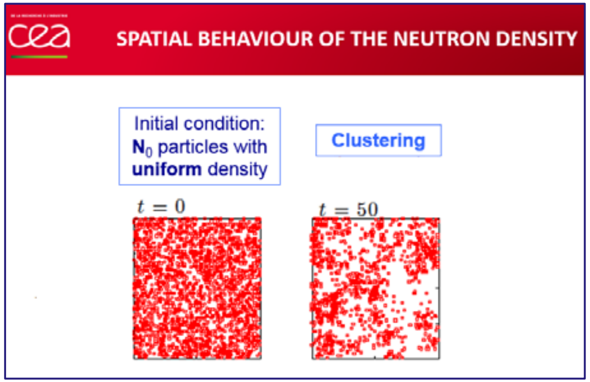
- **Complete analysis and uncertainty quantification of first series of CaSPER measurements.**

- **Publish**
  - o Journal – Yes
  - o ICSBEP?

Future Work

- **Design/Execute a second series of research reactor measurements**
  - o “New and Improved” configurations (based on lessons learned).
- **Simulations with different MC codes with correlated physics of fission (and multiplicity distributions).**
- **Explore experiment design for measuring spatial behavior (clustering).**





Questions?

BACKUP SLIDES

PuBe contribution to results

- May artificially increase calculated efficiency