LA-UR- 11-04130

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Title: SPENT FUEL CHARACTERIZATION USING THE DIFFERENTIAL DIE-AWAY SELF-INTERROGATION TECHNIQUE

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Intended for: 52ND ANNUAL INMM MEETING
Palm Desert, CA
USA
17-21 July, 2011

Los Alamos
NATIONAL LABORATORY
EST. 1943

SPENT FUEL CHARACTERIZATION USING THE DIFFERENTIAL DIE-AWAY SELF-INTERROGATION TECHNIQUE

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ABSTRACT

This paper summarizes the development of the Differential Die-Away Self-Interrogation Technique (DDSI) as a non-destructive assay (NDA) method to measure the fissile mass present in 17x17 pressurized water reactor (PWR) spent fuel assemblies. The Monte Carlo N-Particle eXtended transport code, MCNPX [1], was used to create a library of 64 spent fuel assembly models [2] for simulations purposes within the modeled DDSI geometry, in order to study the detector response to assemblies of varying burnup (BU), initial enrichment (IE), and cooling time (CT). The comprehensive range of these parameters was intended to reflect the range of possible spent fuel assemblies encountered at various facilities worldwide, and the resulting isotopic complexity within those samples. The purpose of modeling is to relate the DDSI detector response to the given fissile mass. Based on this quantitative relation, fissile mass in spent fuel can then be measured experimentally. This paper outlines the DDSI detector configuration, and the determination of two viable ratios, the late gate doubles-to-singles (D/S) ratio and the late-to-early-gate doubles $(L/E)_D$ ratio, which both track with the fissile content of the assemblies. A ^{239}Pu-effective fissile mass concept was used as the basis for quantifying fissile mass, and relating such masses to the ratios. Both ratios were heavily dependent on BU, CT and IE of the assemblies and exhibited similar trends with the salient structure depending on IE. Multiplication within the assembly was used as a key intermediate parameter to develop a predictive model for effective mass values based on the ratios obtained from simulation. Using this model, there was a maximum of 6% deviation across the library between the true effective mass and the predicted effective mass based on the D/S ratio. This work is part of a larger effort sponsored by the Next Generation Safeguards Initiative (NGSI) to develop an integrated instrument, comprised of individual NDA techniques with complementary features, that is fully capable of determining Pu mass in spent fuel assemblies [3].

Spent Fuel Characterization using the Differential Die-Away Self-Interrogation Technique (DDSI)

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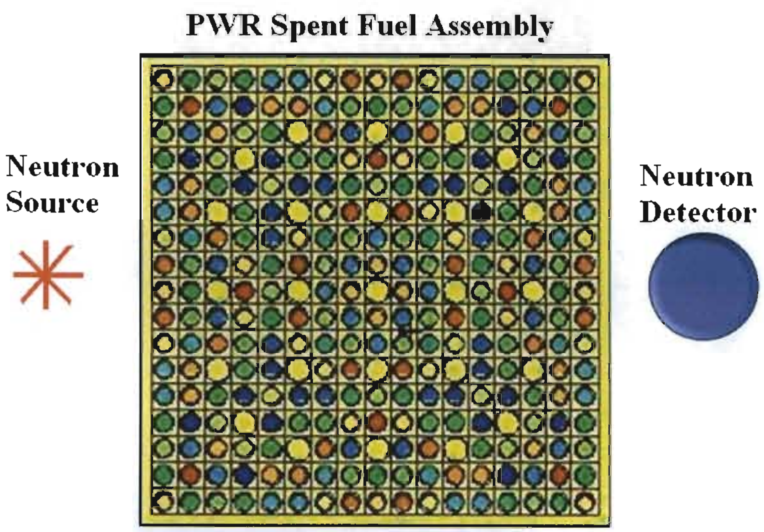
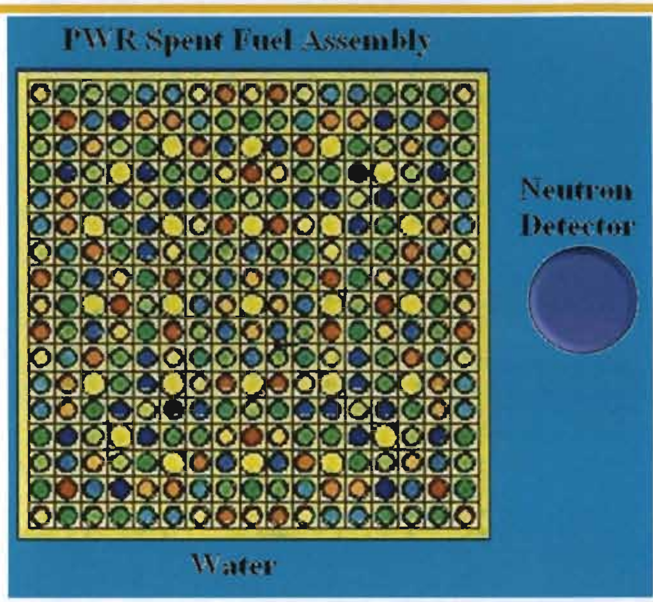
INMM 52nd Annual Meeting, Palm Desert, CA, USA,

July 17-21, 2011

Quantifying Fissile Content:

Active Interrogation vs. Self-Interrogation

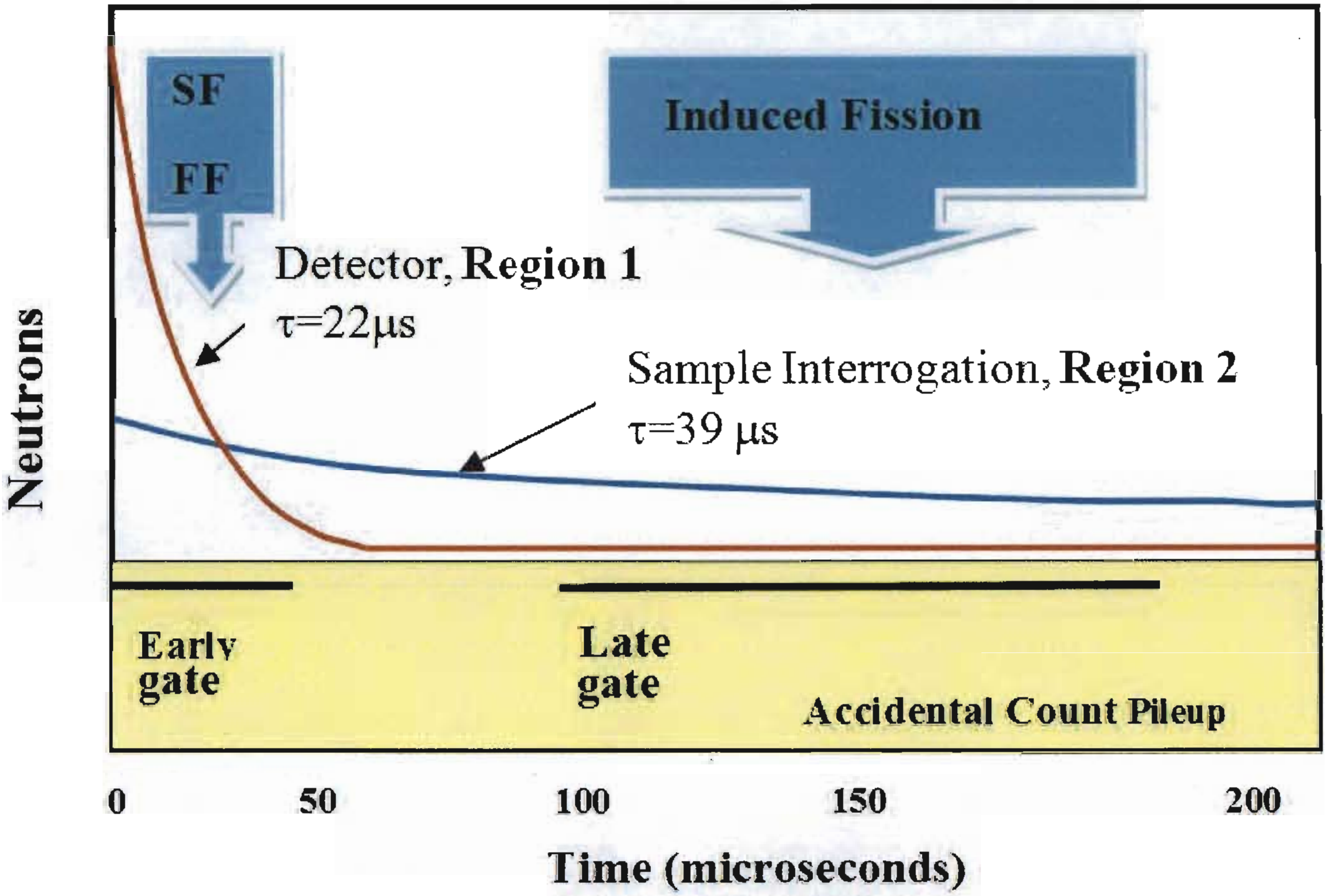




- **External neutrons source** induces fission in assembly
- **Detector** measures SF and IF neutrons
- Induced fission response **proportional to fissile content** in assembly

- **Internal SF neutrons** provide source neutrons
- **Reflected thermal neutrons** induce fissions
- Induced fission response **proportional to fissile content** in assembly

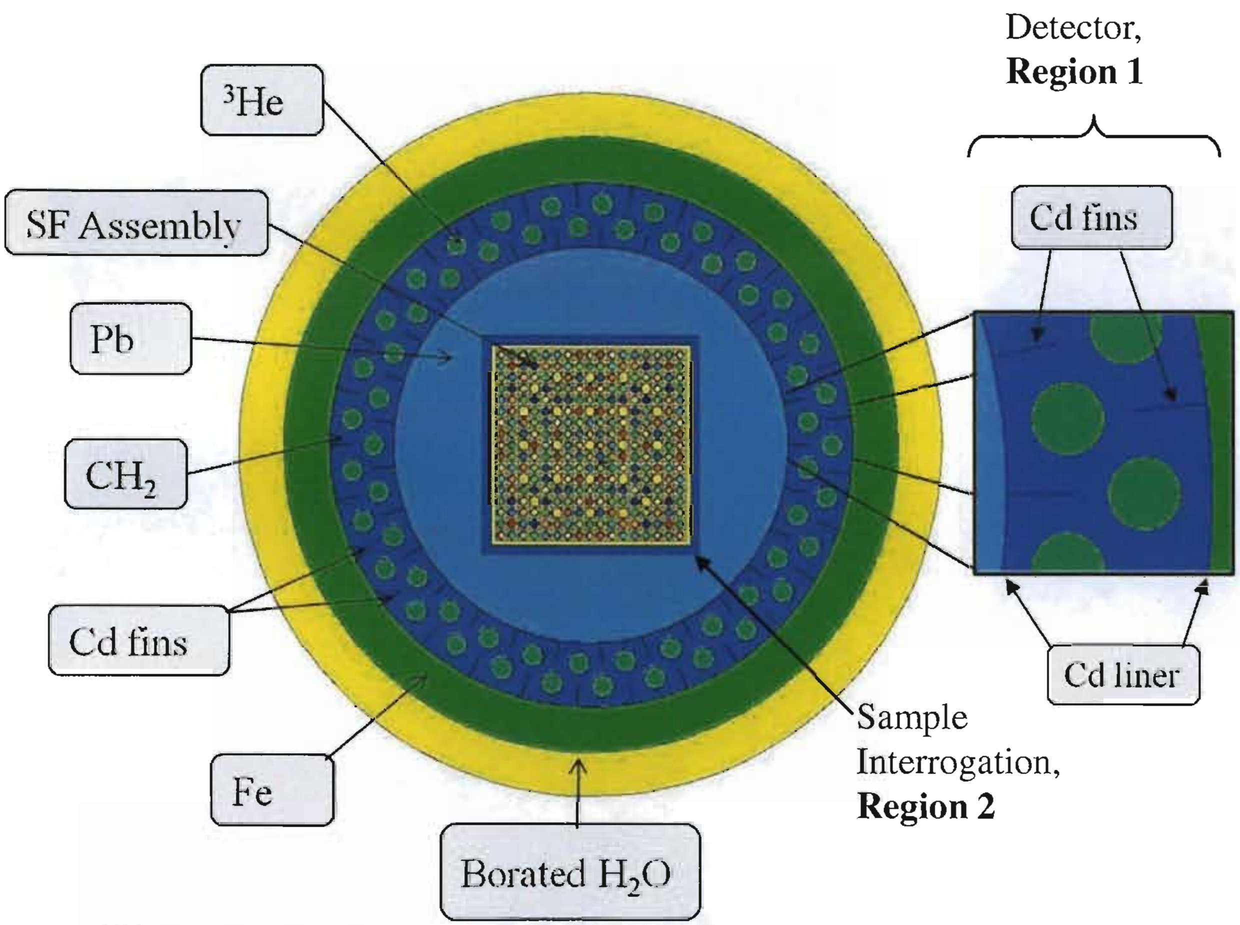
DDSI Time Concept



Achievements:
A Modeling Study: Fissile Measurements using DDSI

- DDSI detector preliminary design
- Detector response obtained for wide range of PWR assemblies
- Two viable ratios extracted to measure effective fissile content in SF
- Multiplication-based parameterization used to establish fit between effective fissile mass and DDSI ratio
- Maximum of 6% deviation between true effective mass and predicted effective mass, using this fitting approach

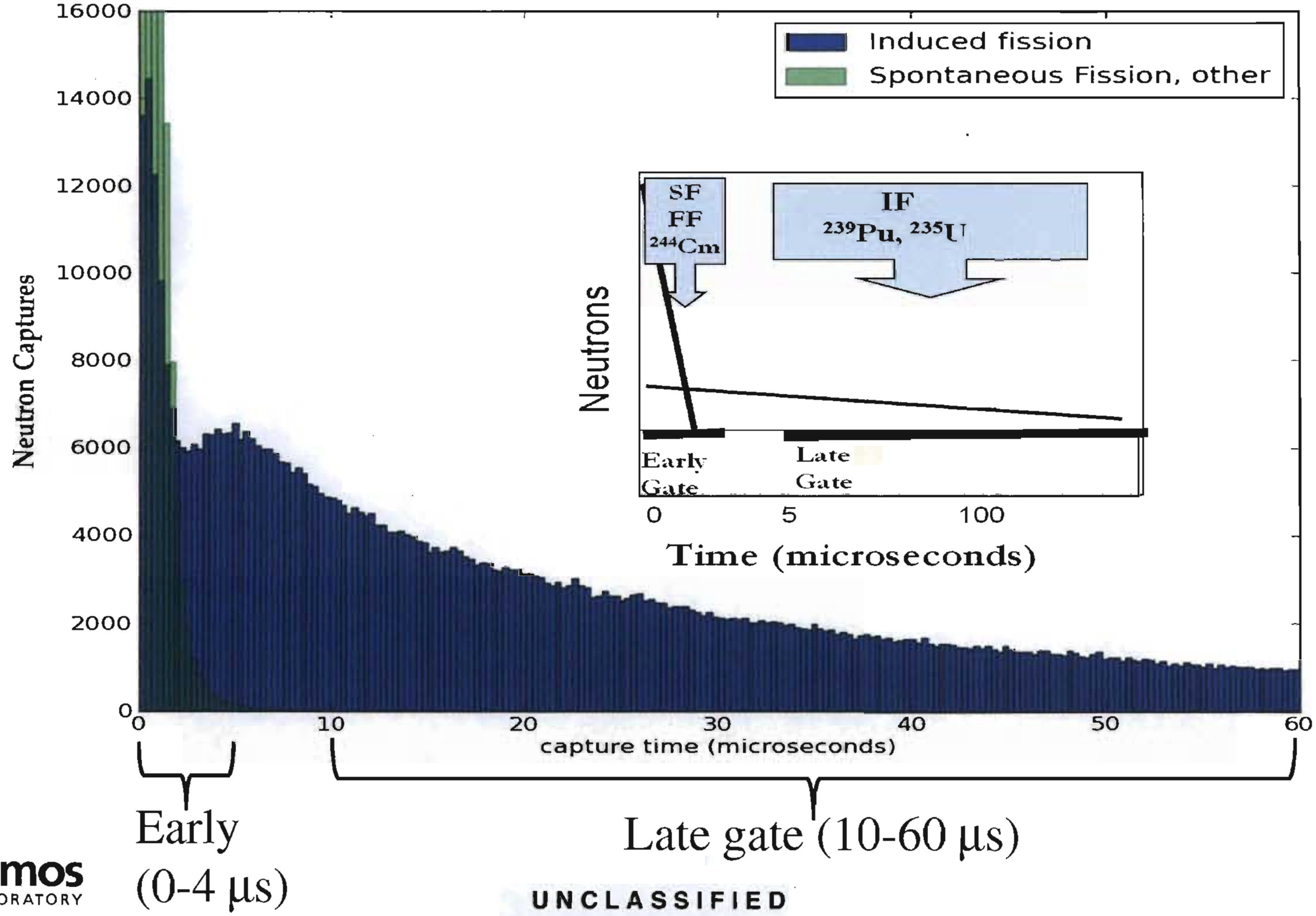
Differential Die-away Self-interrogation (DDSI) for Spent Fuel



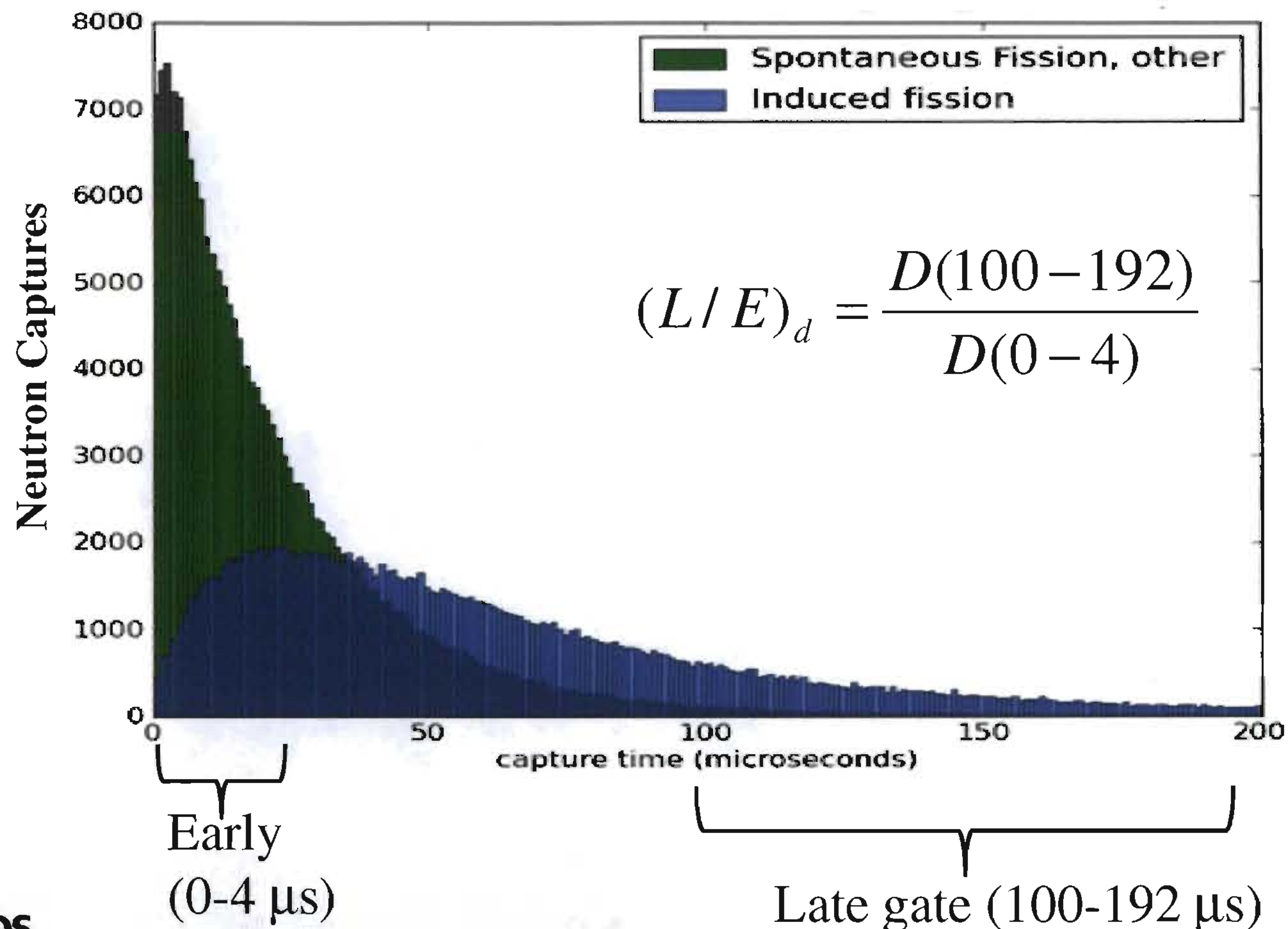
DDSI Concept:

- Dual region detector
- Detector region: short τ
- Interrogation region- long τ
- List mode enables correlated counting in time domain

Neutron Capture Time Distribution in Liquid Scintillator

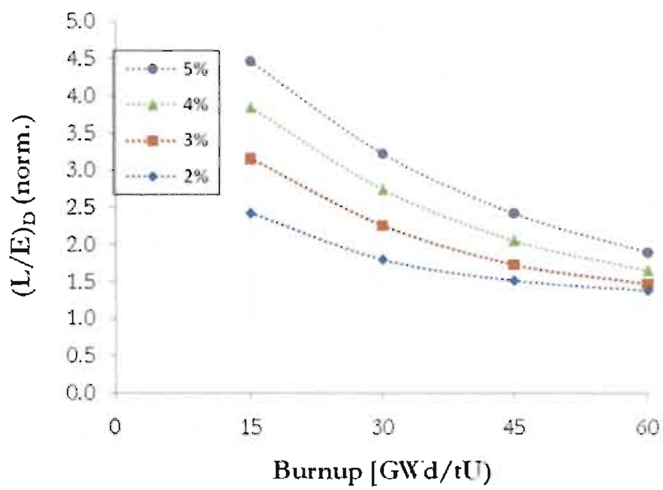


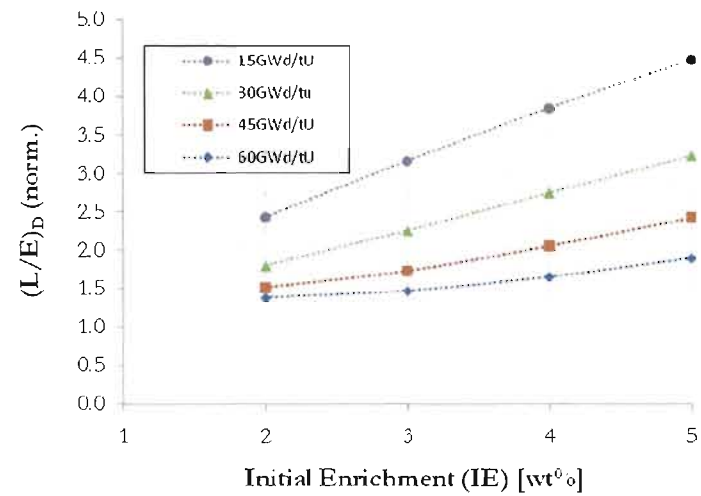
Neutron Capture Time Distribution in ^{3}He design

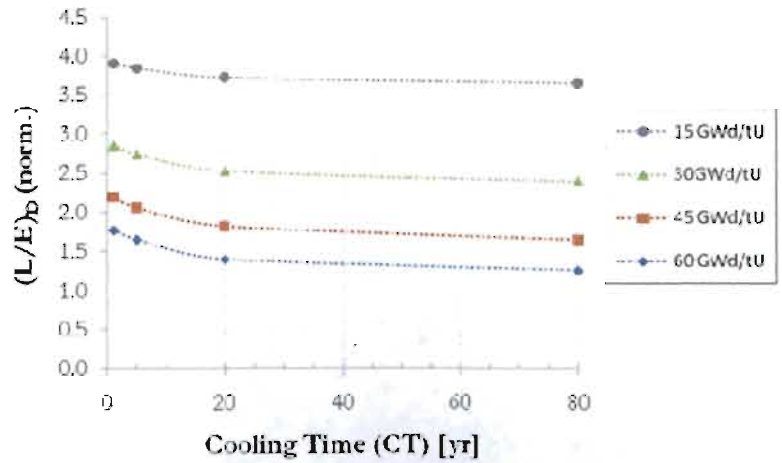


$$(L/E)_d = \frac{D(100-192)}{D(0-4)}$$

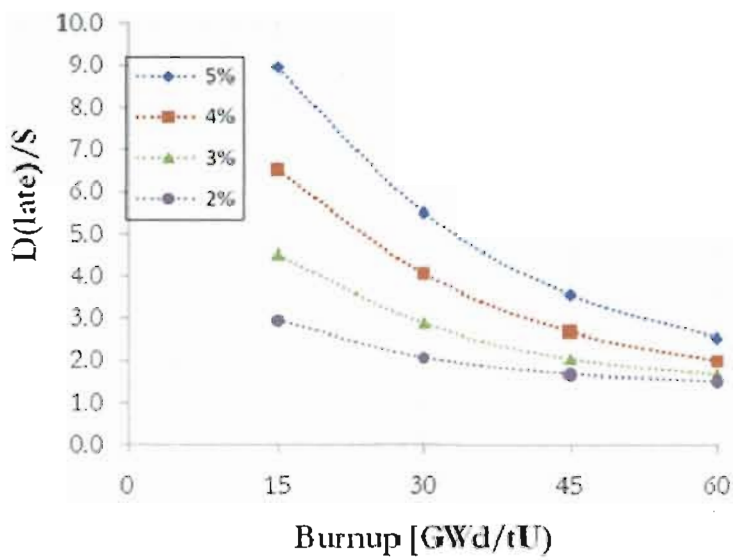
Trends in Late-to-Early-Gate Ratio with SF Parameters





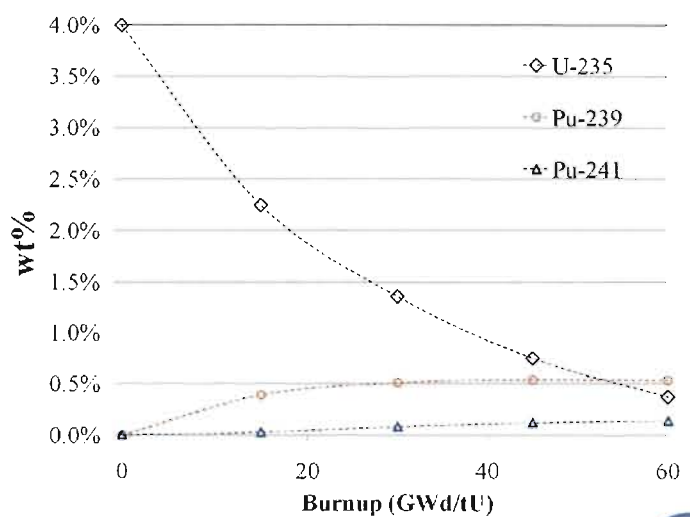


Trends in Doubles-to-Singles Ratio with SF Parameters



- D/S ratio tracks with multiplication
- Multiplication tracks with fissile content

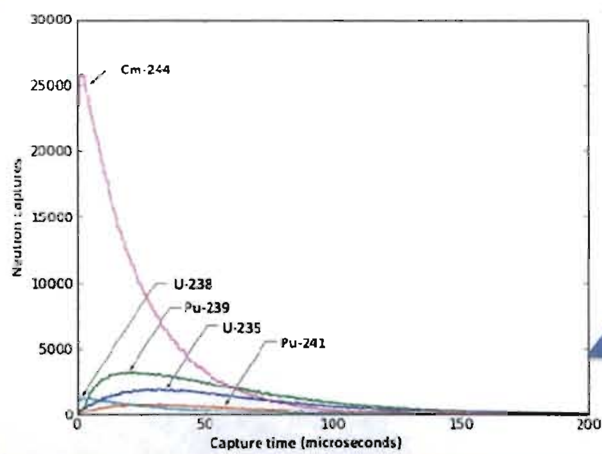
Effective Fissile Mass Concept



$$^{239}Pu_{eff\_DDSI} = C_1\,^{235}U + ^{239}Pu + C_2\,^{241}Pu$$

C_1 and C_2 are dimensionless weighting coefficients

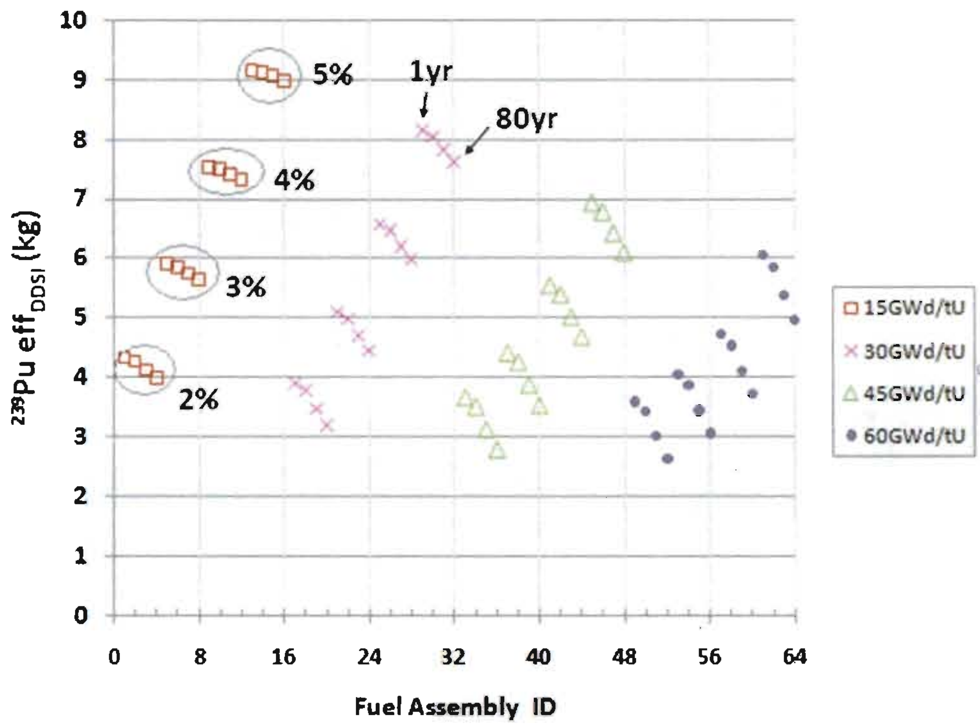
C_1 and C_2 obtained using enhance PTRAC feature of MCNPX



Enhanced PTRAC *MCNPX* feature shows unique time response from ^{235}U and ^{239}Pu. Gates selected using this information and used to weigh contribution of each isotope toward total signal.

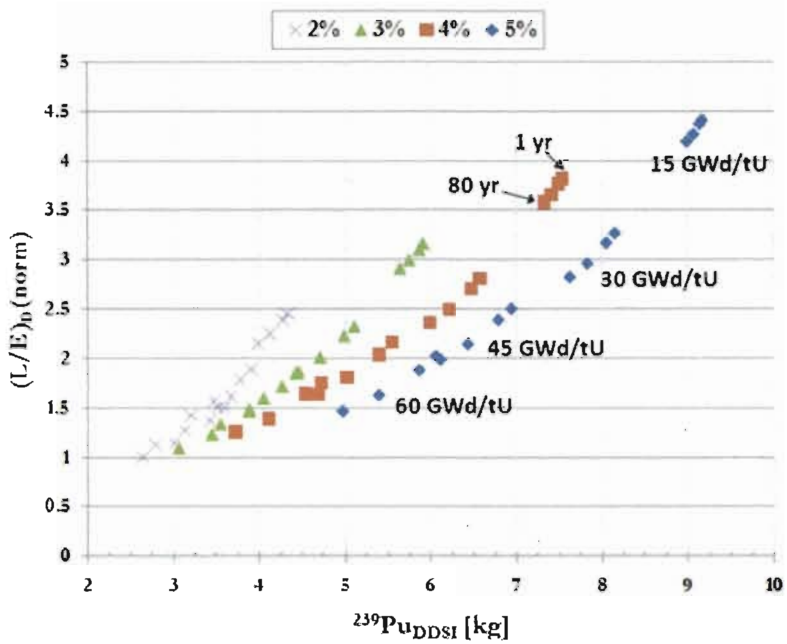
^{239}Pu Effective Masses for LANL Assembly Library

- **^{239}Pu effective mass** depends heavily on BU, IE, and to a lesser extent on CT
- **C_1=0.36**
- C_1 range: [-4.9%, 2.35%]
- **C_2=1.10**
- C_2 range: [-2.4%, 1.2%]



Late/Early Gate Ratio vs. ^{239}Pu Effective Masses

$$(L/E)_d = \frac{D(100-192)}{D(0-4)}$$



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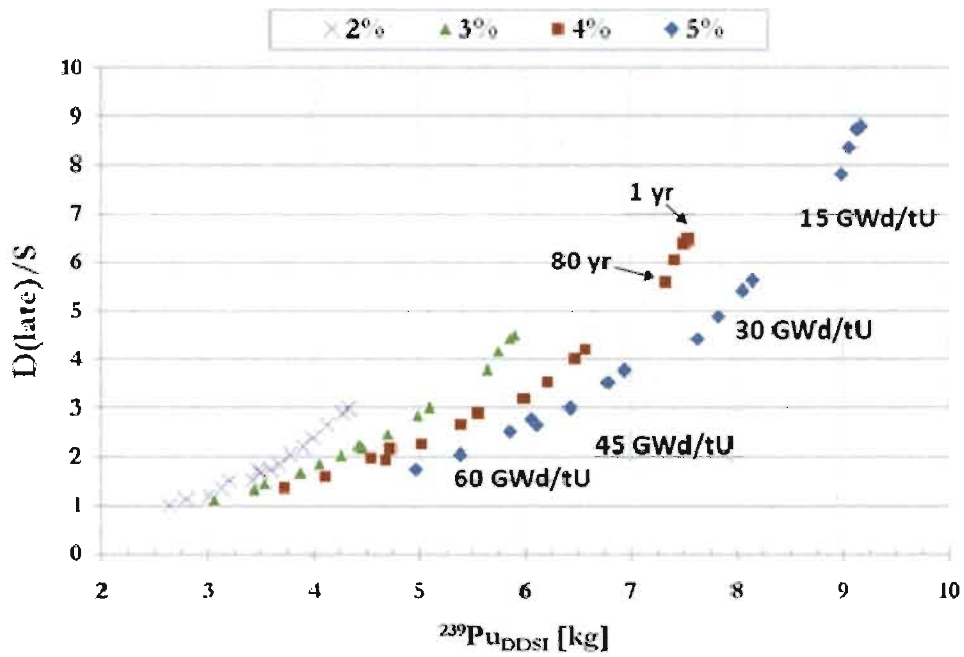
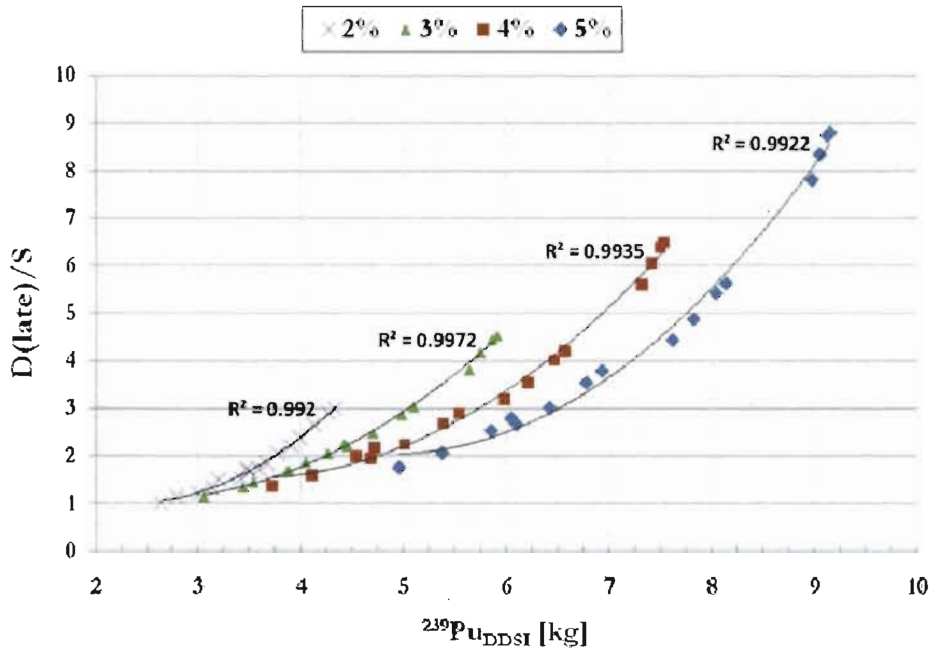
Late Gate Doubles/Singles vs. ^{239}Pu Effective Mass

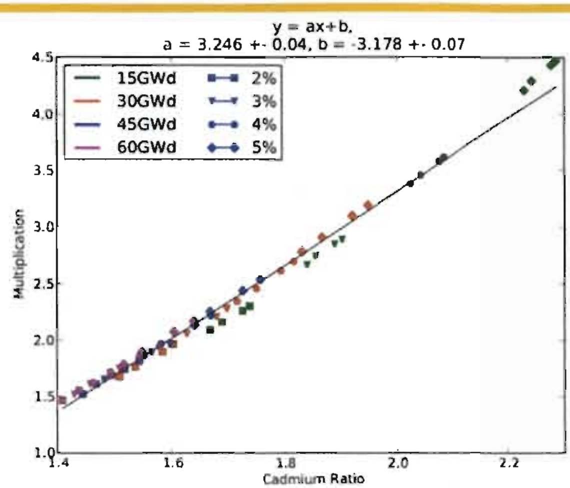
$$\text{Fissile Ratio} = \frac{D(100-192)}{\text{Singles}}$$

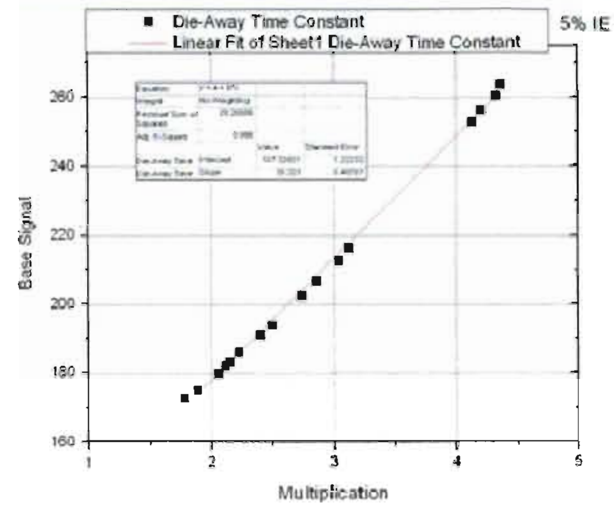


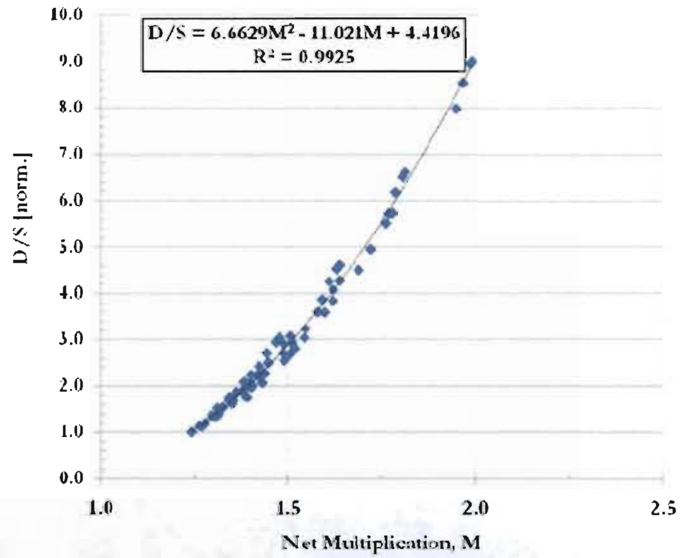
Data Fitting: Parameterization based on Multiplication



Multiplication







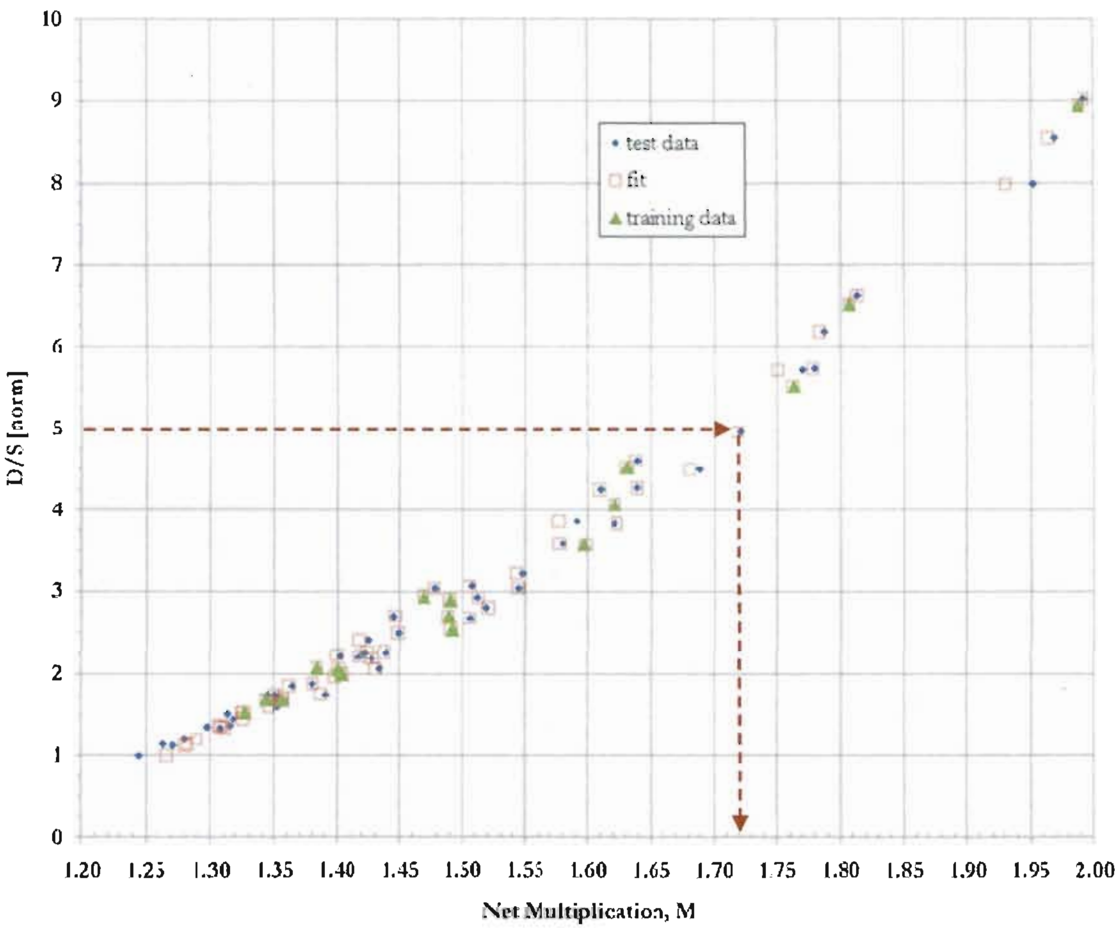
(1) $(D/S)=a\,(M)^2+b(M)+c$

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

(3) $D=\dfrac{F\varepsilon^2 f_d M^2}{2}\left[\nu_{s2}+\left(\dfrac{M-1}{\nu_{i1}-1}\right)\nu_{s1}(1+\alpha)\nu_{i2}\right]$

(4) $(D/S)=\beta\, M\,[1+(M-1)\,\kappa\,(1+\alpha)]$

D/S vs. Net Multiplication



(D/S)=a (M)²+b(M)+c

	5%	4%	3%	2%
a	8.5628	9.099	8.4417	5.6403
b	-16.932	-18.015	-14.892	-5.8111
c	8.7641	9.3621	6.3548	-0.6878
R^2	1	1	1	1

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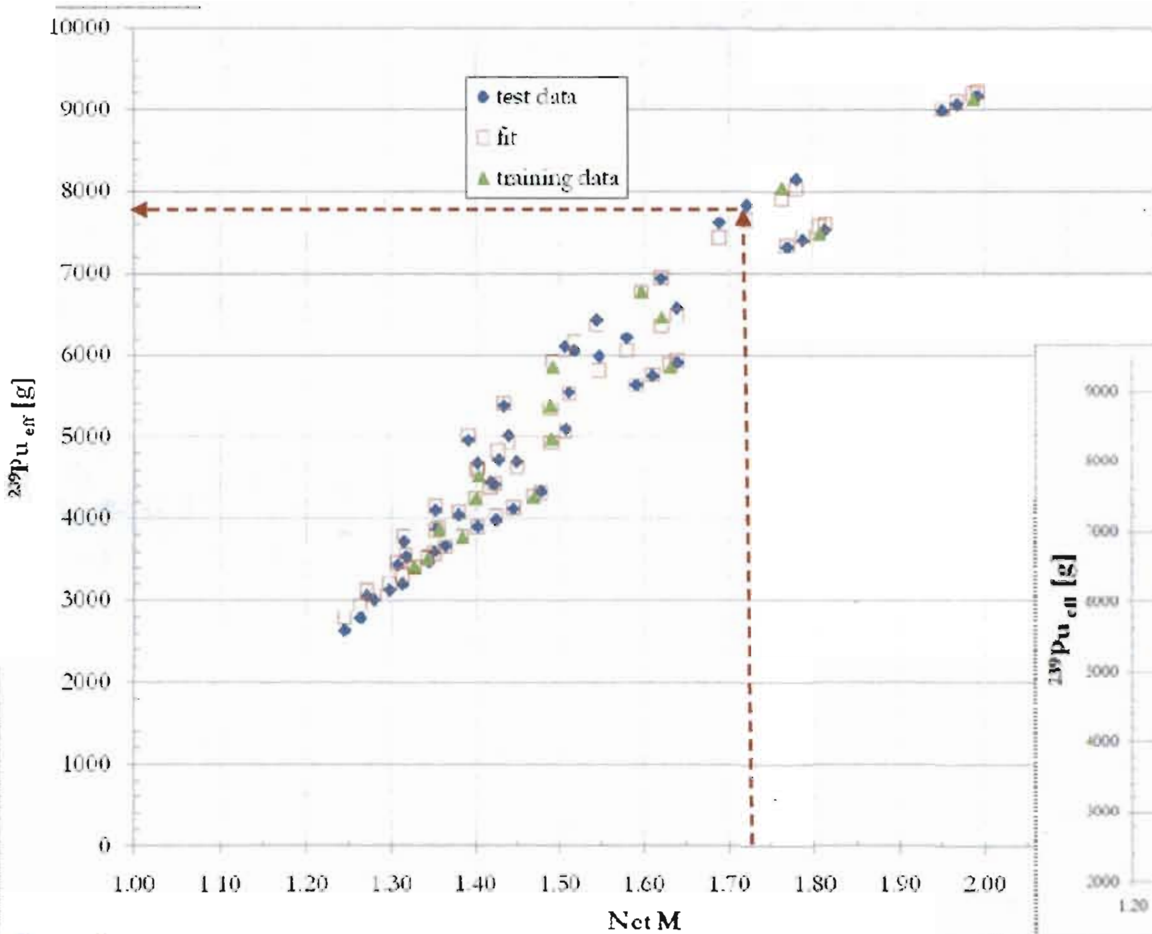
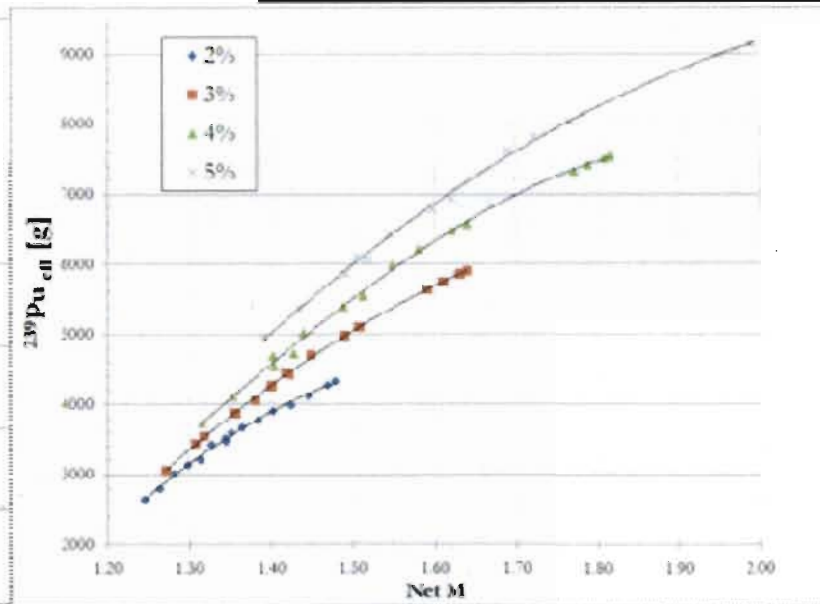
Effective mass vs. Net Multiplication

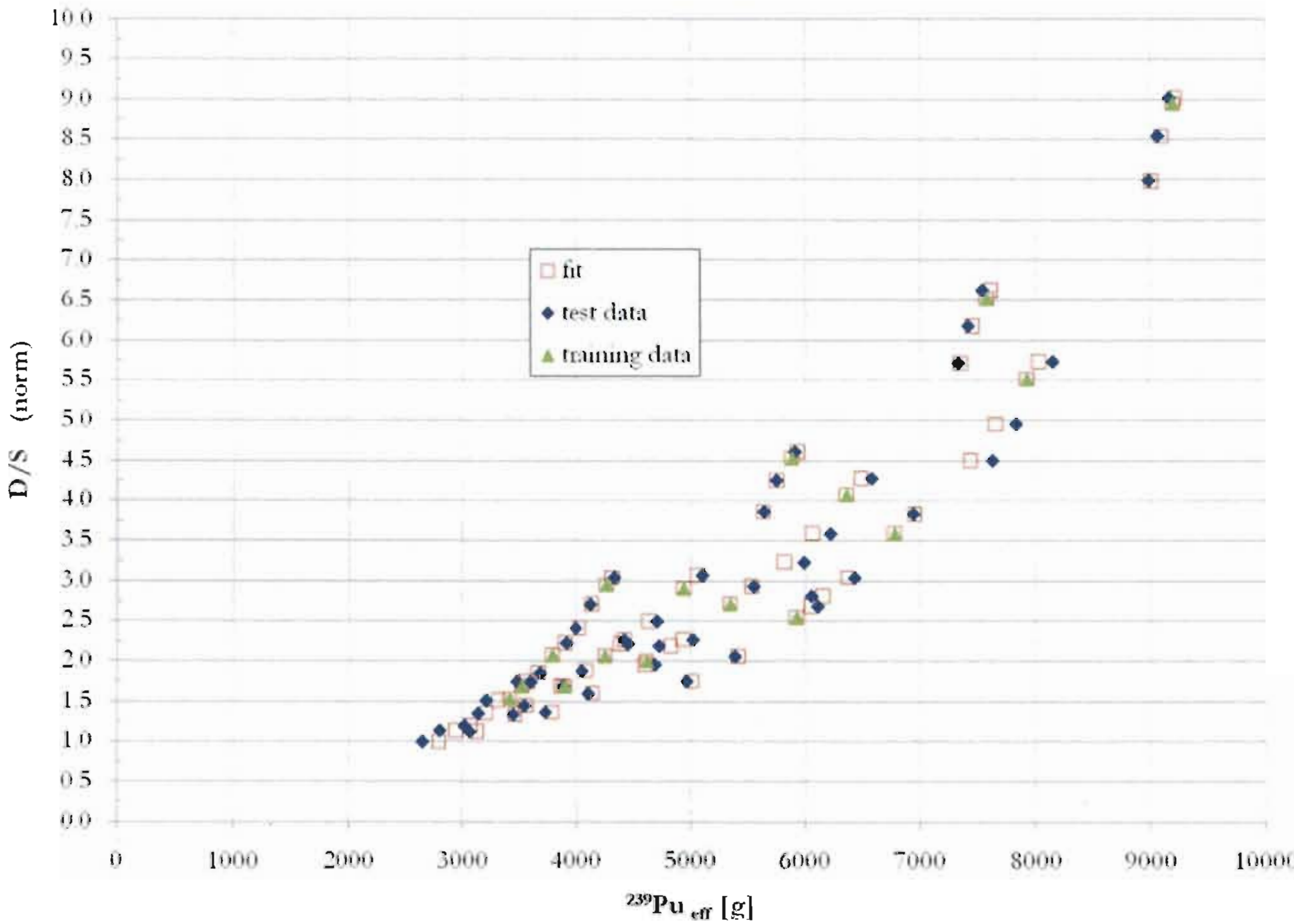


$$(5)\quad M = \frac{d \cdot Pu239eff}{1 + e \cdot Pu239eff} + 1$$

	5%	4%	3%	2%
d	5.86E-05	6.81E-05	7.11E-05	6.33E-05
e	-4.9E-05	-4.8E-05	-5.7E-05	-9.9E-05



Combined Fit Results



- Max error between fit and actual data is ~5.6% for least fissile case (2% IE, 60GWd/tU BU, and 80-yr CT)

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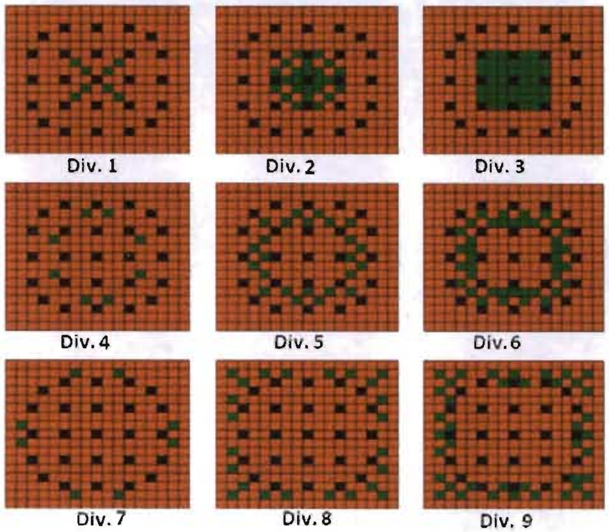
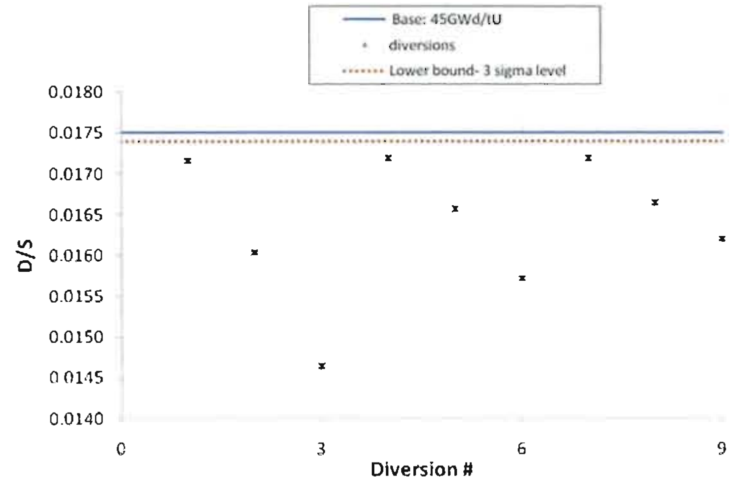
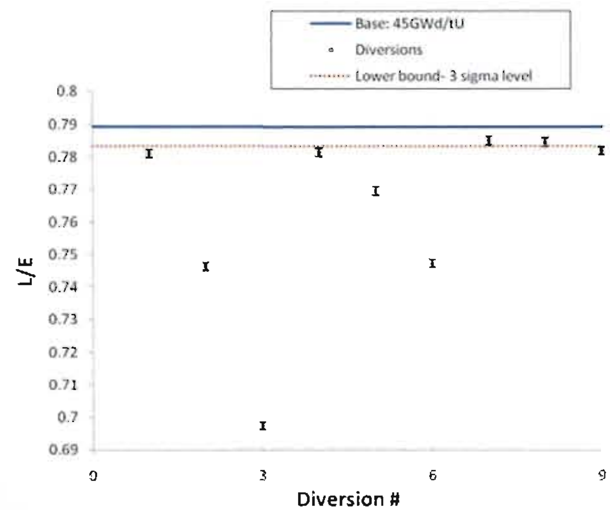
Partial Defect Detection







- (D/S) ratio sensitive to the removal of 3% or greater of fuel pins

Uncertainty in Counting Statistics

- Singles: $$\frac{\sigma_S}{S} = \frac{1}{\sqrt{S.t}}$$
- Doubles: $$t = \frac{D + 2.(S^2 G)}{D^2 \left(\frac{\sigma_D}{D}\right)^2}$$

Pre-delay, Tp	Gate width, G	assay time, t	D/S norm	L/E norm
20	32	124 .26 [sec]	1.66	1.26
60	32	996.04 [sec]	2.13	1.62
100	96	1.74 [hr]	2.71	2.06

Summary

- Two DDSI ratios which track effective fissile content have been established
- Large dynamic range from least to most fissile assembly in library compared to PNAR- FC
- Parametric fit approach has been proposed to quantify effective fissile content from measured DDSI ratio
- D/S response can detect 3% or greater fuel pin diversion
- Partial defect evaluation
- Feasibility ^{235}U and ^{239}Pu discrimination

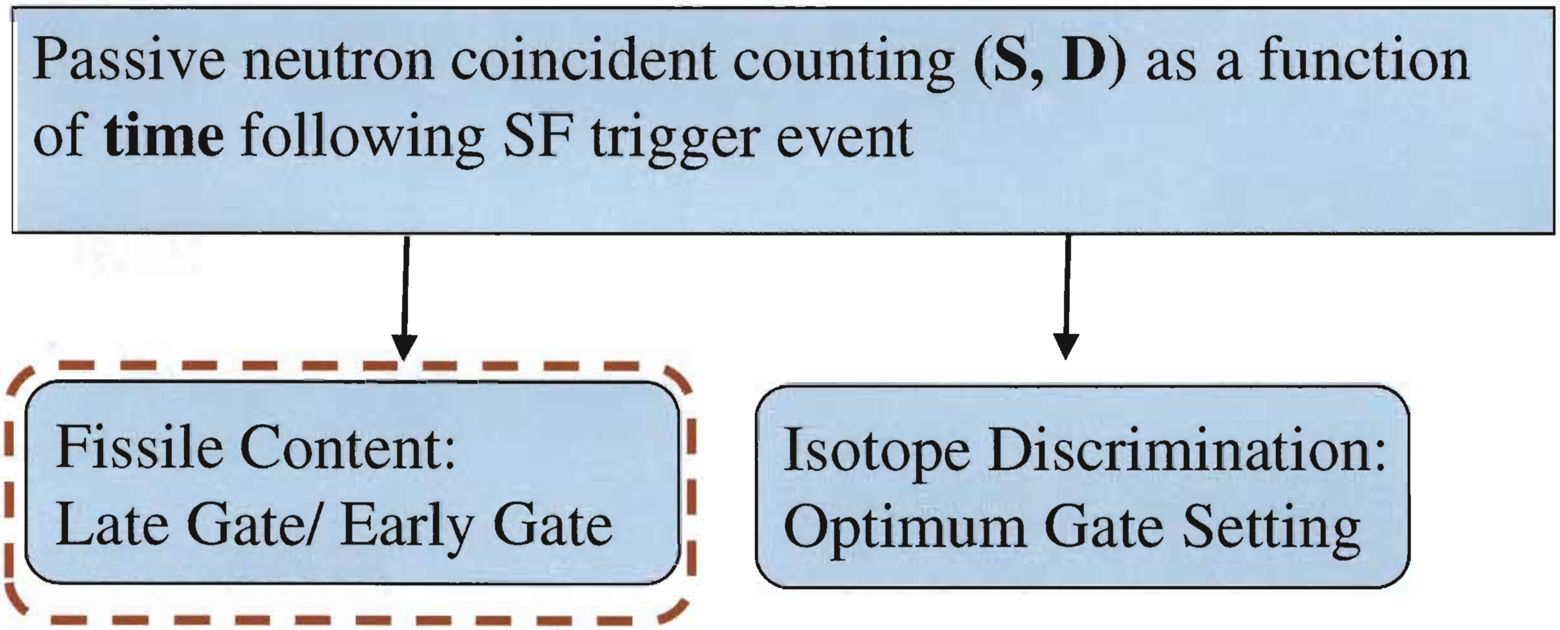
Questions?

The authors would like to acknowledge the support of the Next Generation Safeguards Initiative (NGSI), Office of Nonproliferation and International Security (NIS), National Nuclear Security Administration (NNSA).

Extra Slides

Differential Die-away Self-interrogation (DDSI) for Spent Fuel

- Spontaneous neutron emission within spent fuel induces fission in fissile isotopes present (^{235}U, ^{239}Pu, ^{241}Pu)

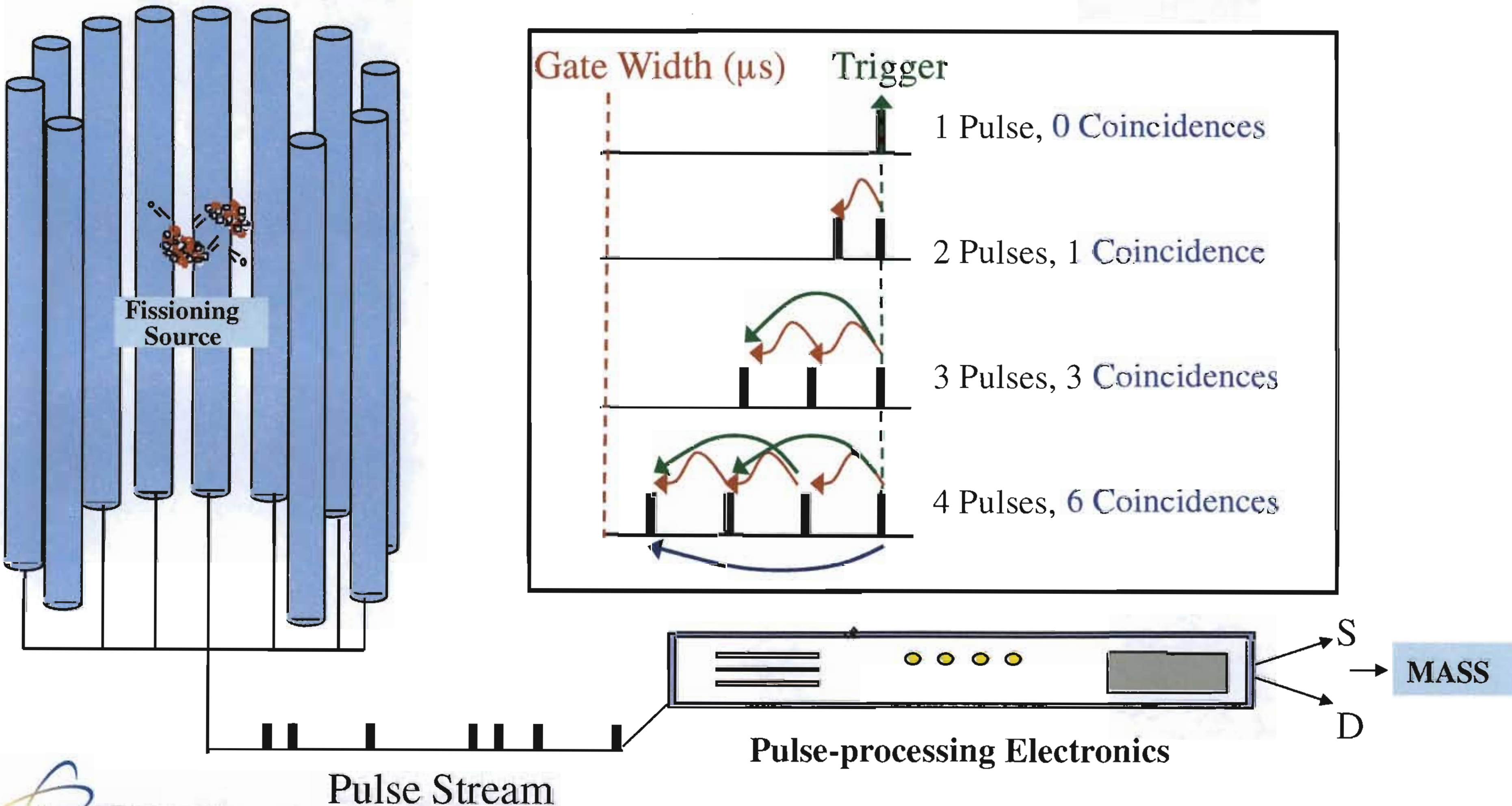


NDA Self-interrogation Techniques for Pu Verification

Self-interrogation of Spent Fuel Assembly

PNAR	DDSI	MULTIPLICITY
-Uses Cd ratio	- Early to late gate doubles ratio	-counts S, D, T
-Fission chamber design: low efficiency	- ^{3}He or Liquid Scintillator- high efficiency	-^{3}He or Liquid Scintillator- high efficiency
-^{3}He design: high efficiency	**- Total fissile measurement**	**-Total fissile measurement**
-Total fissile measurement	- Measure ^{235}U & ^{239}Pu	-Measure ^{235}U & ^{239}Pu
- Integrate for isotopic ratios		

Primer on Neutron Coincidence Counting



List Mode Data Analysis

- Each neutron event time and amplifier is stored in computer file
- multiple gates,
- variable pre-delays
- Post data analysis in computer
  - event triggered analysis - Multiplicity
  - Clock triggered analysis - Feynman