Validation of the Stable Period Method Against Analytic Solution

T. MAKMAL[1,2], N. HAZENSPRUNG[1], S. DAY[2]

1) NUCLEAR PHYSICS AND ENGINEERING DIVISION, SNRC, YAVNE, ISRAEL
2) DEPARTMENT OF ENGINEERING PHYSICS, MCMASTER UNIVERSITY, ONTARIO, CANADA

Part I: Introduction

- The determination of the reactivity worth is essential to assure safe and reliable operation of the reactor system.
- Two practical approaches to calculate the reactivity worth of the control rods:
    - The rod-drop method
    - The stable period method ("SPM").
- The SPM is more accurate and official due to the next advantages of this method:
    - The standard power monitoring equipment is available.
    - The detector location has no effect on the measurements.
    - The method allows measurement of the differential reactivity worth.
- The main disadvantage of this method is the time considerations.

Part I: Introduction

- The reactivity of the system is related to the stable reactor period, expressed by the inhour equation:

$$\rho = \frac{l}{T} + \sum_{i=1}^{6} \frac{\beta_i}{1 + \lambda_i \cdot T}$$

- The period (T), can be found by the ratio of the power (P) within known time (t).

$$P(t) = P(0) \cdot e^{t/T}$$

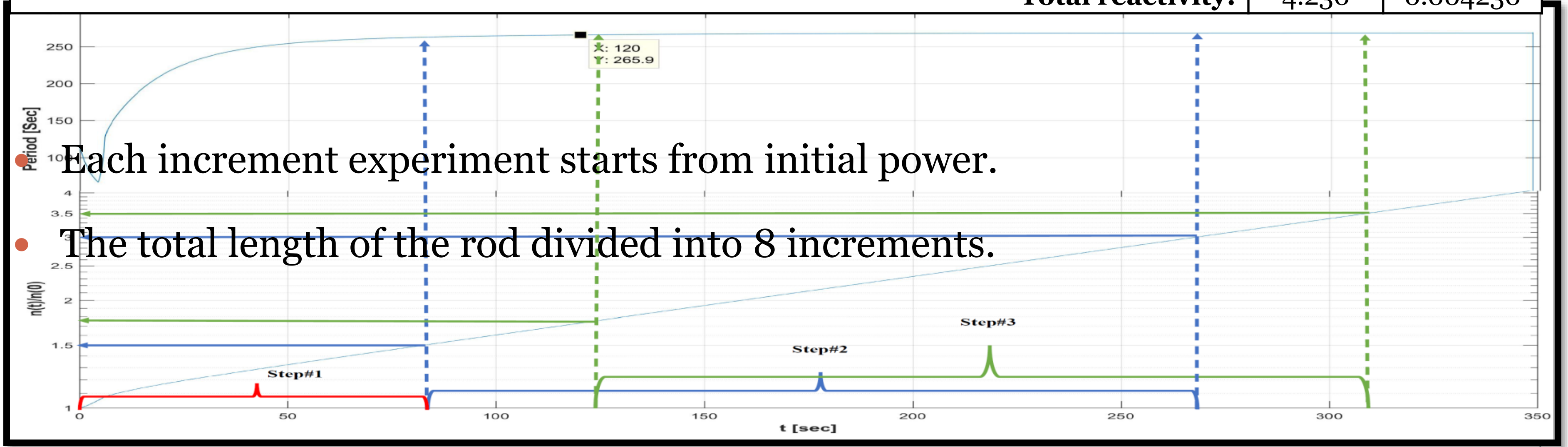
- The analysis considers two RRs, Each uses different practical applications of the SPM for calibrating the regulating rod.
- Following the calibration of the regulating rod, cross-calibrate the high-worth shim-safety rod bank has been estimated.

Part I: The objective of this study

- The objective of this study is to estimate a conservative uncertainty for the stable period method using the official procedure of the two selected reactors.
- The following sources were considered as contributing to the overall uncertainty:
  - uncertainty on parameters used in calculations;
  - uncertainty due to the procedure, and
  - uncertainty related to delayed neutron effectiveness coefficient.

Part II : Doubling time Method

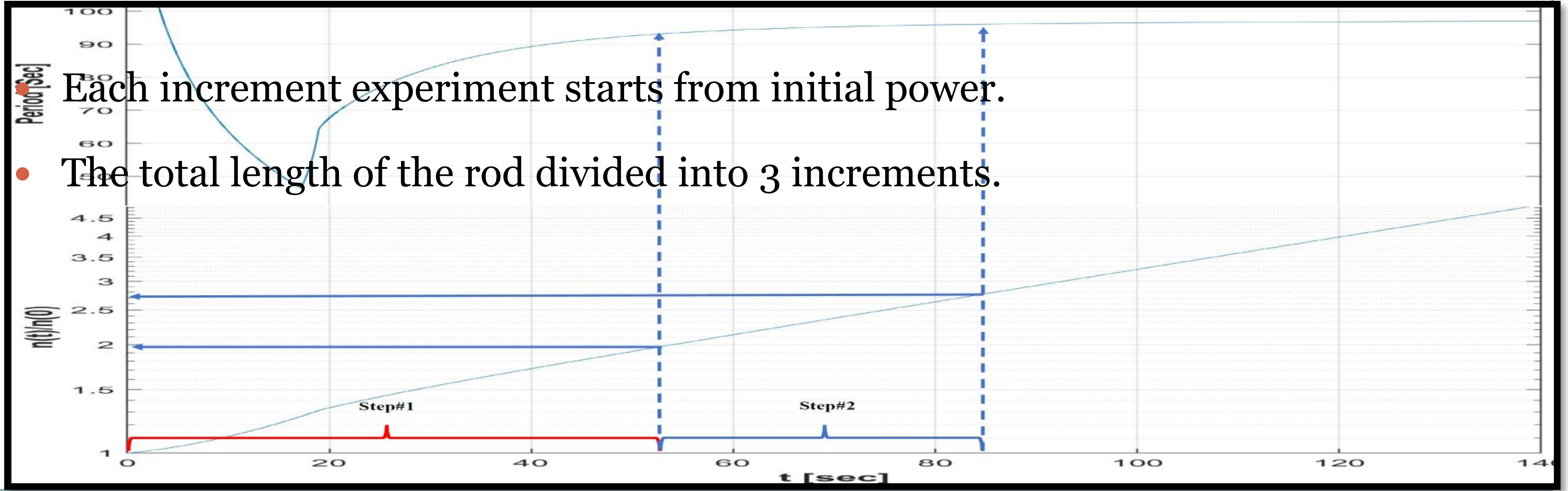
Increment#	Rod Position		Doubling Times		Average Doubling Time [sec]	Average Period [sec]	Rod Worth [mk]	Rod Worth [dk/k]
	Initial[%]	Final[%]	T_1[sec]	T_2[sec]				
1	0	19.3	122	126	124.0	178.9	0.488	0.000488
2	19.3	28.1	128	132	130.0	187.6	0.468	0.000468
3	28.1	36.55	102	103	102.5	147.9	0.572	0.000572
4	36.55	45.1	93	93	93.0	134.2	0.620	0.000620
5	45.1	54.5	88	88.7	88.4	127.5	0.646	0.000646
6	54.5	60.9	185	187	186.0	268.3	0.342	0.000342
7	60.9	71.4	128	127	127.5	183.9	0.476	0.000476
8	71.4	100	93	94	93.5	134.9	0.617	0.000617
						Total reactivity:	4.230	0.004230



- Each increment experiment starts from initial power.
- The total length of the rod divided into 8 increments.

Part II : 30 second method

Increment#	**Rod Position**		**Period [sec]**	**Rod Worth [mk]**	**Rod Worth [dk/k]**
	Initial[%]	Final[%]			
1	0	33.5	94.5	0.761	0.00076
2	33.5	56.5	79.1	0.872	0.00087
3	56.5	90	64.5	1.012	0.00100
			Total reactivity:	2.645	0.00264



- Each increment experiment starts from initial power.
- The total length of the rod divided into 3 increments.

Part III: Uncertainty per Increment (1/2)

uncertainty on parameters used in calculations;

The random errors per increment combined using linear error propagation with the assumption that all individual uncertainties are independent.

Total Random Uncertainty per Increment		
Method	**Absolute uncertainty [mk]**	**Average relative uncertainty**
Doubling time	**0.04**	**7%**
30 Seconds	**0.09**	**10%**

Uncertainty on Time Measurement		
Method	Absolute uncertainty [mk]	Average relative uncertainty
Doubling time	0.01	2%
30 Seconds	0.03	4%

Part III : Uncertainty per Increment (3/3)

Uncertainty associated with the method:

- Deviation between the experimental to the numeric solution was found by fitting the experimental period to the numeric reactivity.

Reactor A – Doubling Time Method

Increment#	Experimental Period [sec]	Numeric Reactivity [mk]	Experimental Reactivity [mk]	Reactivity deviation [mk]	Reactivity Percentage Deviation
1	178.89	0.483	0.488	-0.005	-0.96%
2	187.55	0.464	0.468	[illegible]	[illegible]

Method	Average Absolute uncertainty [mk]	Average relative uncertainty
Doubling time	**-0.006**	**-1.1%**
30 Seconds	**-0.012**	**-1.4%**

Reactor B – 30 Seconds Method

Increment#	Experimental Period [sec]	Numeric Reactivity [mk]	Experimental Reactivity [mk]	Reactivity deviation [mk]	Reactivity Percentage Deviation
1	94.54	0.745	0.761	-0.016	-2.16%
2	79.09	0.860	0.872	-0.012	-1.38%
3	64.48	1.004	1.012	-0.008	-0.74%

Part IV :Propagation of Errors (1/2)

- The random error propagation on sum of (N) increments calculated by formal linear propagation.

$$Total\ Random\ Uncertainty = \sqrt{\sum_i^N (\Delta\rho_i)^2}$$

Reactor	Absolute uncertainty	Relative uncertainty
A – Doubling Time	0.10 mk	2%
B – 30 seconds	0.16 mk	6%

- The systematic error on sum of (N) increments found by summing the average systematic error on each incremental

$$Total\ Systematic\ Uncertainty = N \cdot \Delta\rho_{Average\ sys'error}$$

Reactor	Absolute uncertainty	Relative uncertainty
A – Doubling Time	0.05 mk	1%
B – 30 seconds	0.04 mk	3%

Part IV :Propagation of Errors (2/2)

Cross-calibrate the bank of high-worth shim-safety rods:

- The regulating rod reactivity value is used to cross-calibrate the shim rods.
- The shim-safety rods calibration carry out by moving an increment of the shim rod and compensating using the already calibrated regulating rod.
- As in the previous analysis, standard error propagation methods are used to estimate the random and the systematic uncertainty components.

Reactor	Relative systematic uncertainty	Relative random uncertainty
A – Doubling Time	1.1 %	±1.4%
B – 30 seconds	1.4 %	±1.7%

Part V :Importance factor (1/2)

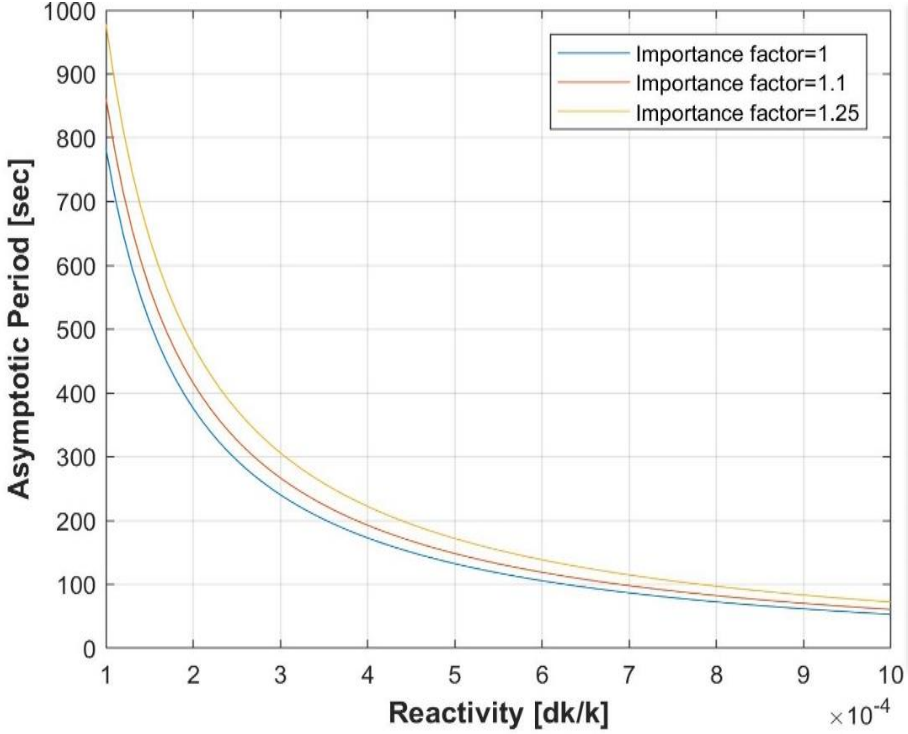
Systematic uncertainty related to delayed neutron effectiveness coefficient:

- Treated separately from the other parameters used in the *SPM* calculations in order to highlight the importance of the uncertainty in this quantity.
- The effectiveness of the delayed neutrons is captured by introducing a scaling factor (γ) on the delayed neutron fraction, $\beta eff \equiv \gamma\beta$, varies from 1.25 to 1.
- The Importance Factor range depends on fuel enrichment, core properties (size and structure) the calculations code and the cross-section library.
- The use of unsuitable importance factor results an additional significant systematic error.

Part V :Importance factor (2/2)

Systematic uncertainty related to delayed neutron effectiveness coefficient:

- To investigate the sensitivity of the importance factor on the rod worth reactivity, a numeric solution estimates the reactivity values between 0.1mk to 1mk for different importance factors.



Reactivity Values [dk/k]	Reactivity deviation between 1.25 to 1.10	Reactivity deviation between 1.25 to 1.00
$3x10^{-4}$	-14.7%	-27.3%
$3.5x10^{-4}$	-15%	-27.9%
$4x10^{-4}$	-15.3	-28.5%
$4.5x10^{-4}$	-15.9%	-29.1%
$5x10^{-4}$	-15.9%	-29.8%
$5.5x10^{-4}$	-16.2%	-30.4%
$6x10^{-4}$	-16.5%	-31.1%
$6.5x10^{-4}$	-16.8%	-31.7%
$7x10^{-4}$	-17.1%	-32.4%

Part VI :Conclusions

- Analysis of errors found relatively low values of uncertainties in both methods.
- The major advantage of the “doubling time” method is the intrinsic adjustment of the waiting time to the reactivity insertion .
- Digitalization the process can reduce the uncertainties in terms of the human error on time and power reading.
- The uncertainty on the importance factor represents the largest potential source of systematic uncertainty.
- Monte-Carlo codes can predict this parameter using Meulekamp's method.

Thank You

Questions?