Development of the "Approach to Critical" Experiment Simulation Model for the CONSORT Reactor using LabVIEW.

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Introduction

According to IAEA, as of 2012 nuclear energy contributed 12.3% of the world's electricity.

Why nuclear energy?
- Due to growing energy demand,
- The ever increasing prices of fossil fuels ,
- The need for a carbon free energy source to reduce global warming
- In order to gain energy independence and security of supply.

Nuclear power reactors operators need to have thorough training to ensure plant safety. Nuclear Reactor simulation models are used as teaching tools for nuclear reactor operations.

They therefore help to;
- Understand reactor operational behavior, under both normal and accident scenarios.
- Avert reactor accidents thus providing information for future reactor safety improvements, and
- Provide a memento after shutdown.

The CONSORT Reactor

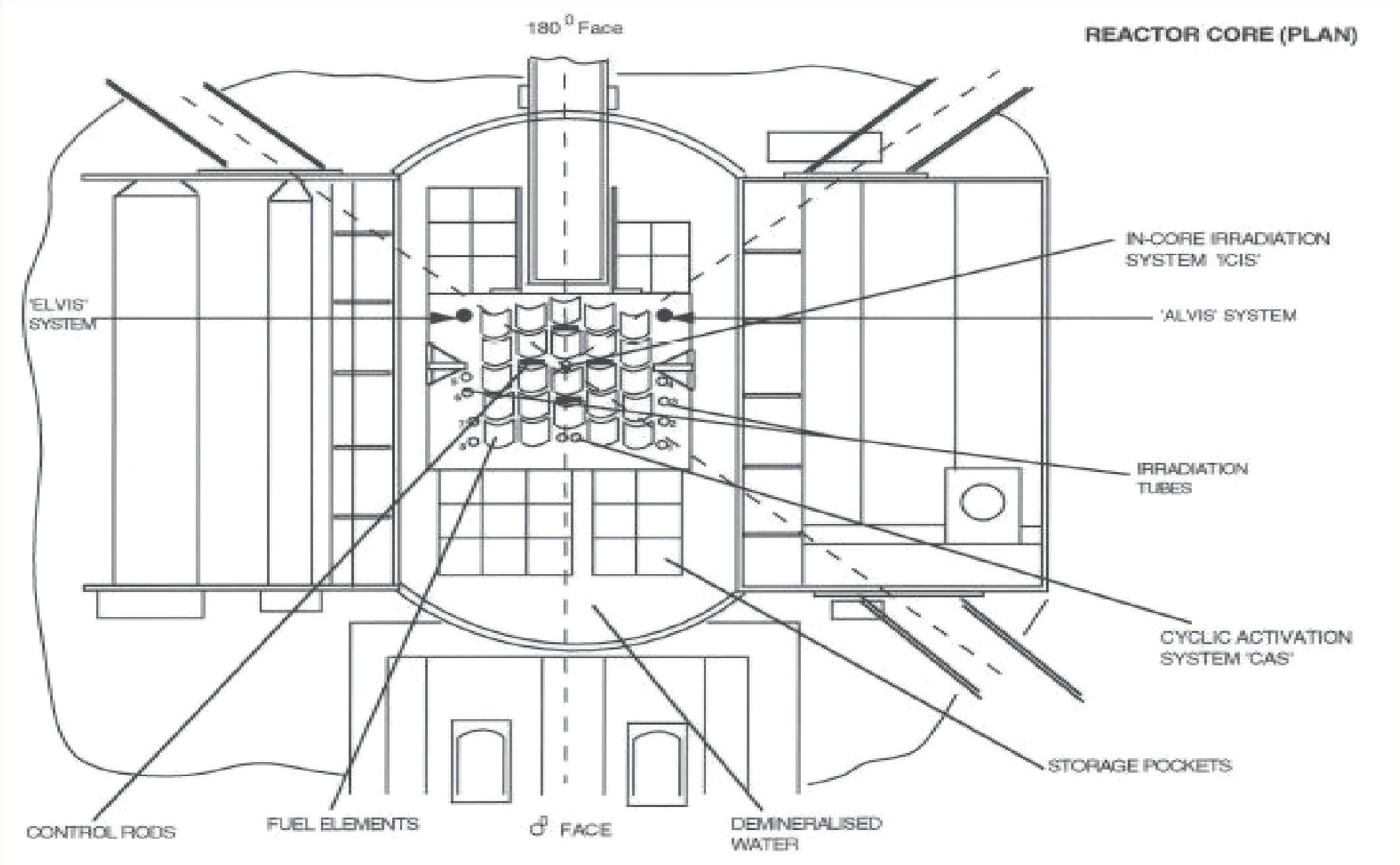


Figure 1: Cross section showing the location of the control rods in the core (Kafala, 2005)

- First went critical in 1965
- 100kW pool-type research
- The core had 24 fuel elements with 12-16 HEU with high purity aluminum clad
- Light water as coolant, moderator, reflector & shield
- A 11.2GBq americium/beryllium neutron source for start-up power
- 3 cadmium and 1 steel control rods

"Approach to Critical" Experiment demonstrates the procedure for taking the reactor to critical operation, balancing the system at low power and increasing the power over a range of powers levels and eventual reactor shutdown. The development of its simulation model was therefore important to enable future students to have comparable training following the CONSORT reactor shut down in 2012.

The Approach to Critical experiment is carried out as a safety measure,
- At the start of the reactor operation, and
- After major plant modifications such as fuel configuration.

Why perform the experiment?
- To determine the control rod height at which the reactor becomes critical and to confirm the balance point.
- To cross check that new fuel has been correctly positioned in the core.

During the **"Approach to Critical"** experiment, reactivity is increased by raising the control rods. At every step of the procedure, the measurement of the neutron detectors is taken and used to predict the control rod height the reactor will become critical.

Methods

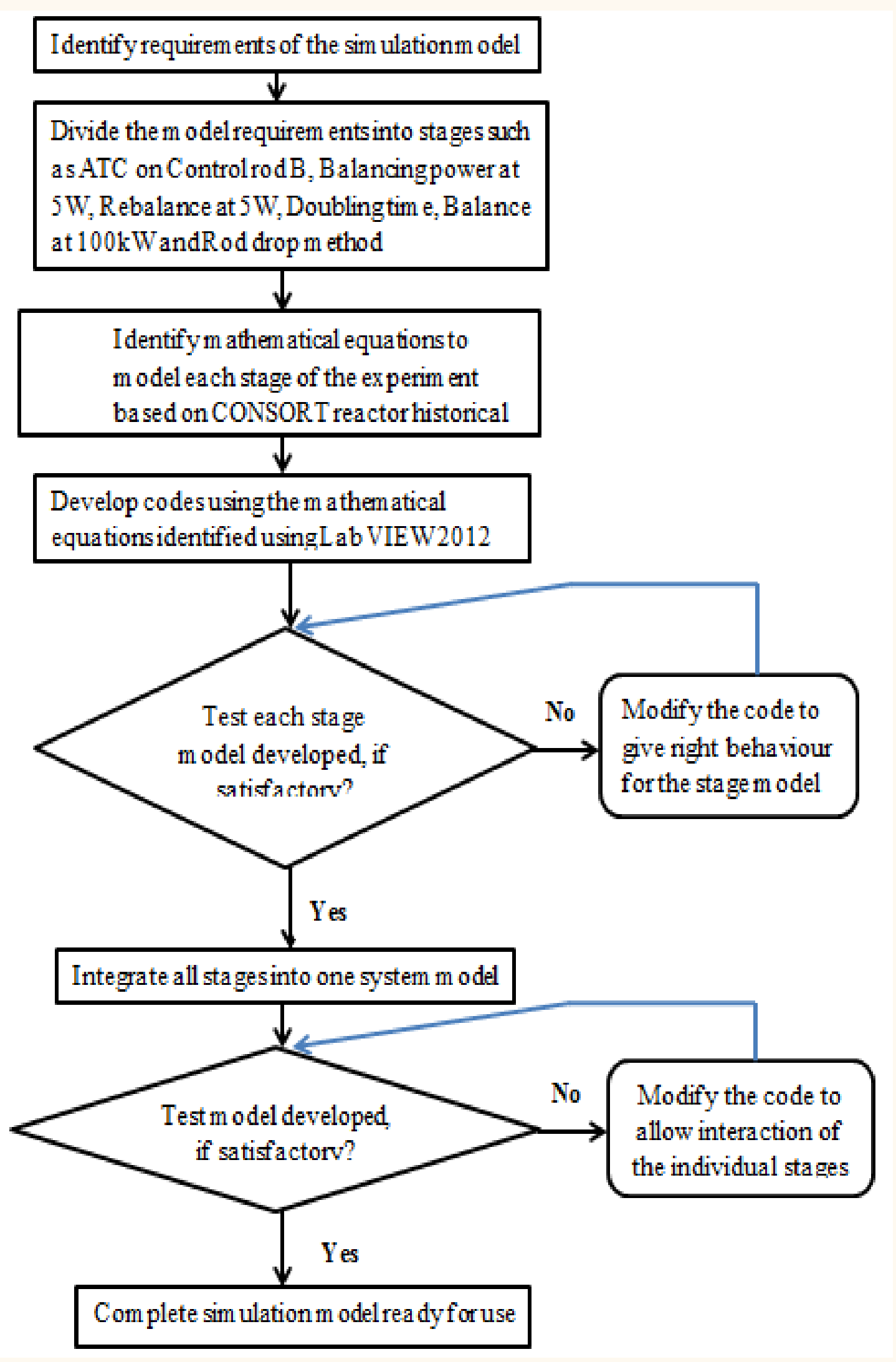


Figure 2: Modulation Process used to develop the simulation model

Simulation Design Assumptions

Reactivity changes only with the movement of controls rods with temperature effects negligible.

Simulation Code

Stage one of the full **"Approach to Critical"** experiment was modeled with control rod A as the primary coarse rod and control rod B as the secondary coarse rod. The three main stages of experiment modeled were;-
1. Approach to Critical on control Rod B, power balance at 5W
2. Doubling time measurement method on control Rod B and power balance at 100kW
3. Rod Drop method on control Rod A at 100kW

The following equations were used to develop the code under the experiment stages above;

1. Approach to Criticalon Control Rod B
Rod worth is the reactivity decrease resulting from the insertion of the control rod.

$$\rho(x) = w_T\left[1 - \frac{x}{H} + \frac{1}{2\pi}\sin\frac{2\pi x}{H}\right]$$

- $\rho(x)$= Excess reactivity (%) at a given height x
- w_T= Total reactivity obtained from inserting the control rod full length
- (Rod B =1.833, Rod A=2.785 and Rod F=0.575)
- $H =$ Height of the core of 60 cm measured in the same direction as x the height at which the control rod is raised.

Neutron Count Rate:

$$\text{Neutroncountrate}/30sec = \frac{10^5}{y}$$

Power Meter Reading: $\mathbf{y = 8 \times 10^{-6}\ x^{1.0406}}$

y = power in watts and x= the count rate per second

2. Doubling Time Measurement Method
Power change due to a step reactivity change was calculated from **"one group of delayed neutron approximation equation"**:

$$n = n_o\left\{\frac{\beta}{\beta-\rho}\ exp\left(\frac{\lambda\rho}{\beta-\rho}t\right) - \frac{\rho}{\beta-\rho}exp\left(-\frac{\beta-\rho}{l_p}t\right)\right\}$$

- n_o is the neutron density at balanced condition before a reactivity step change
- Delay neutron fraction $\beta = 0.0065$,
- Decay constant $\lambda = 0.08s^{-1}$
- Prompt neutron lifetime (for water moderated, enriched uranium reactor) $lp = 0.0001s$
- **Neutron flux density = Power:** $n/n_0 \cong p/p_0$

$$\textbf{Deviation meter measurement} = \left[\left(\frac{\text{Actual power}}{\text{Demanded power}}\right) - 1\right] \times 100\%$$

At power balance: Actual power = Demanded power

3. Rod drop method
Since **"one group of delayed neutron approximation equation"** does not effectively give the correct power decrease after shut down, Power was assumed to decrease with a varying decay constant at specific set times to account for the effect of the different delayed neutron half-lives following shut down. The decay constant values were found by **"trial and error"** method, using the following equation;

$$Decay\ Constant\ (\lambda) = \frac{1}{Mean\ life\ (t_m)}$$

State Diagram

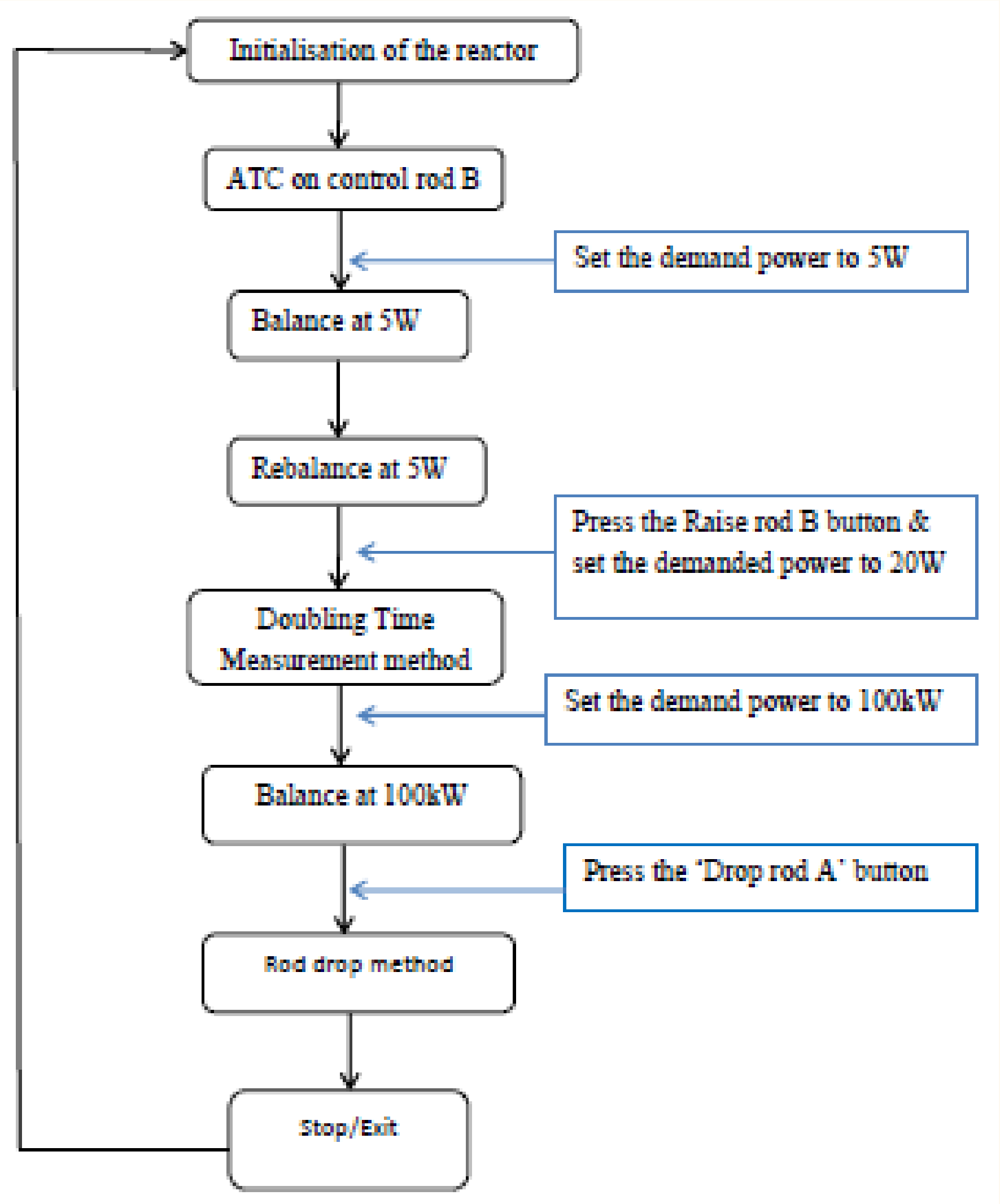
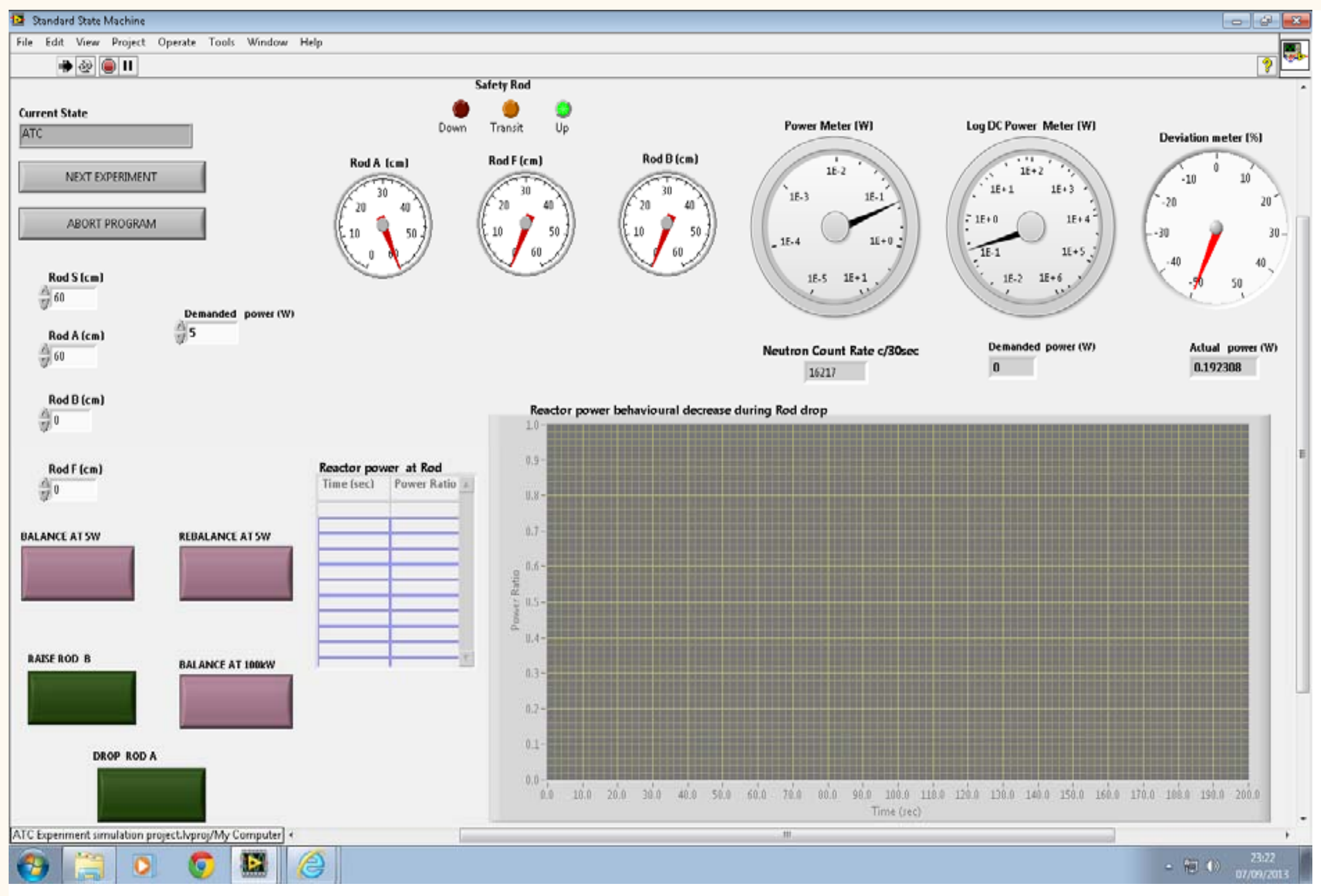


Figure 3: State diagram for the simulation model showing the different stages.

Results



Current State: ATC
Rod S (cm): 60
Rod A (cm): 60
Rod B (cm): 0
Rod F (cm): 0
Demanded power (W): 5
Neutron Count Rate c/30sec: 16217
Demanded power (W): 0
Actual power (W): 0.192308

Figure 4: The "Approach to Critical'' Experiment Simulation Model User interface.

The **"Approach to Critical''** Experiment simulation model for the CONSORT reactor was successfully developed and the results were comparable to the reactor's historical data.

Critical Rod Position

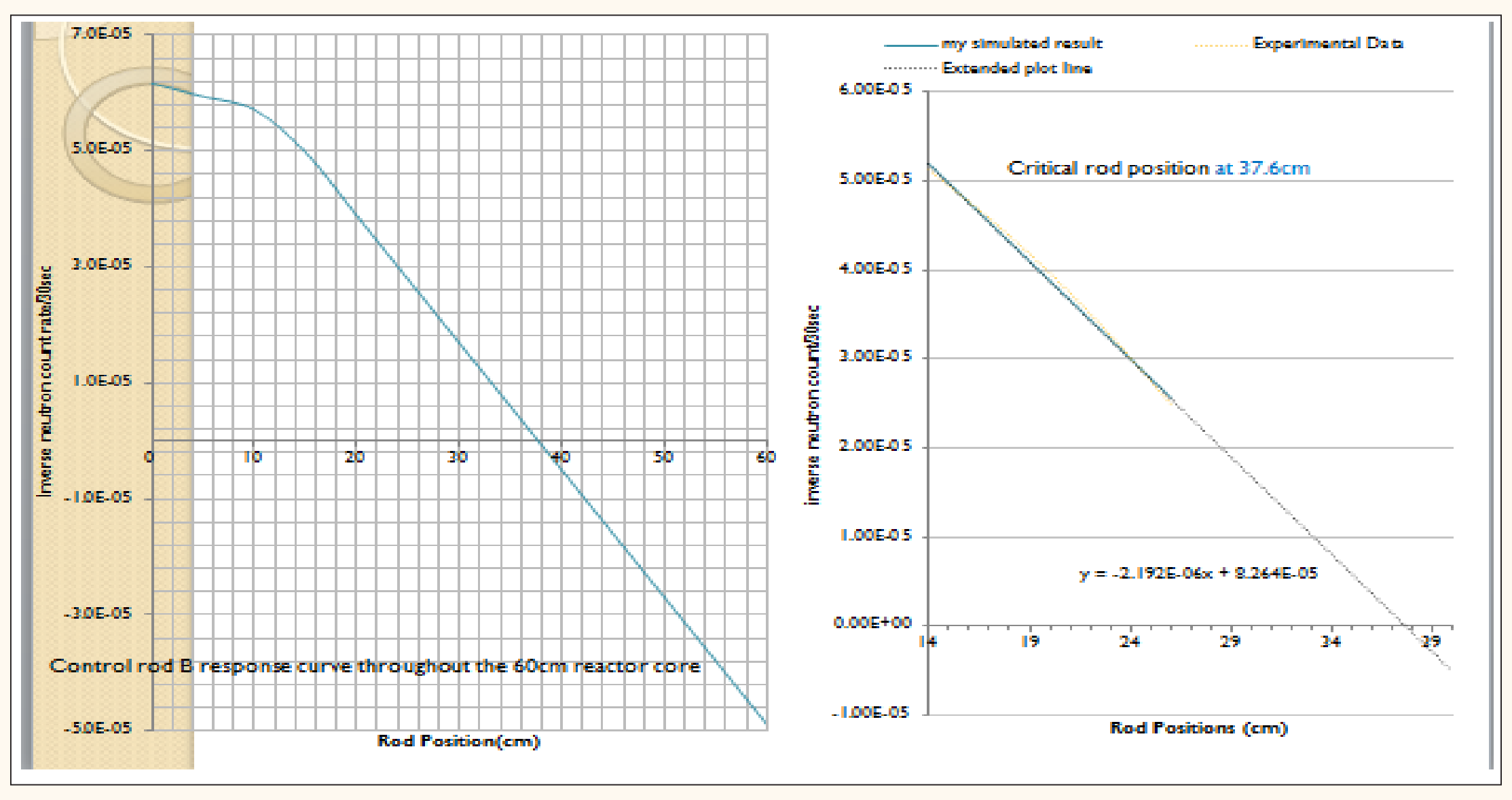


Figure 5: Control rod B response curve throughout the 60cm reactor core and Approach to Critical Curve with a critical rod position at 37.6cm.

Reactor Power increases with increase in rod position and varies inversely with excess reactivity.

2. Step Change of Reactivity

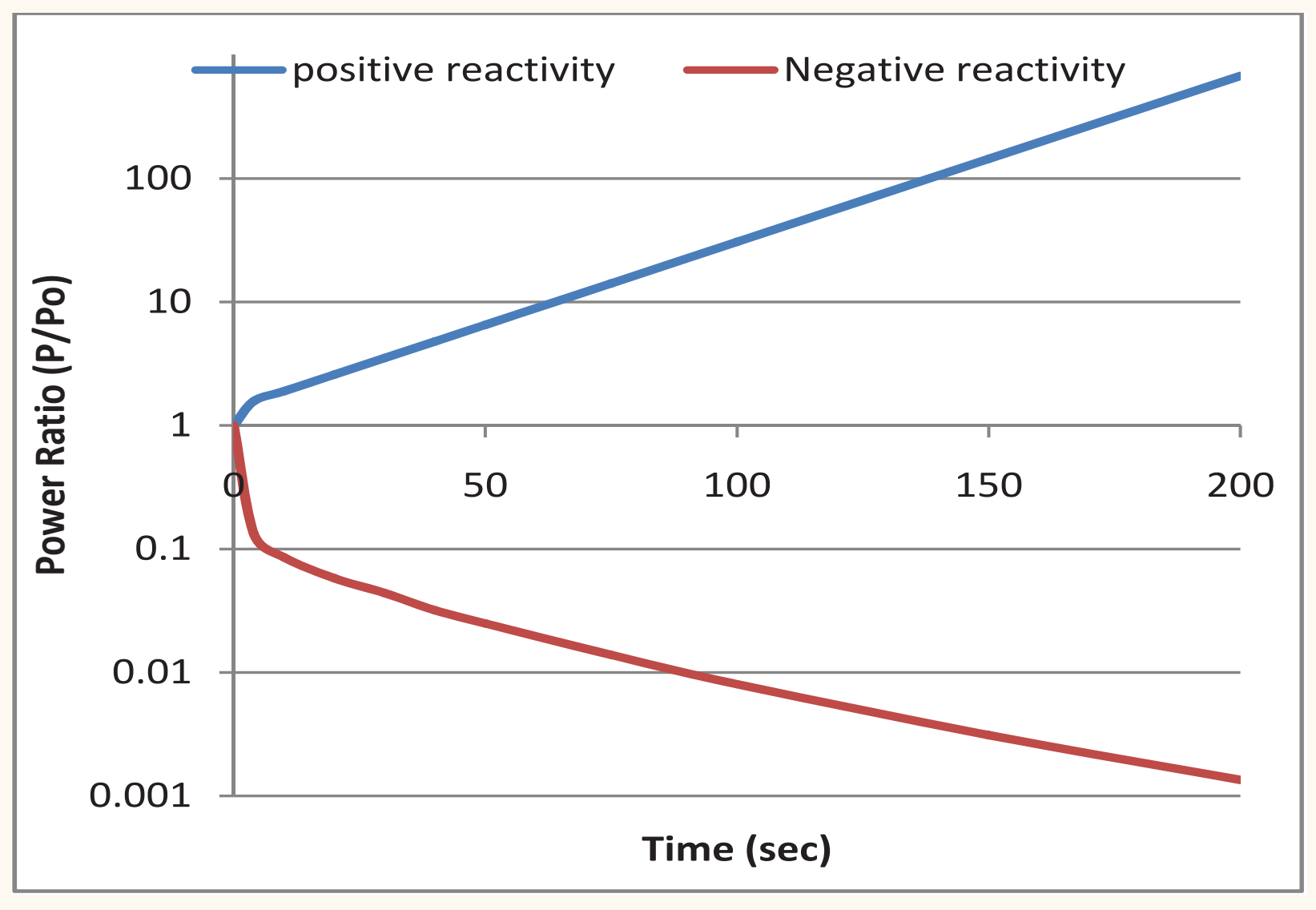


Figure 6: Reactor power behavior in response to a step change in reactivity due to a reactivity insertion of **+0.00181** and **-0.02785.**

- Power vary as a function of time with an exponential factor
- A period is introduced thus doubling time and rod drop method are used for calibrating control rods
- Doubling time of 33 seconds was obtained to give a reactivity of 1.89 % for Rod B

3. Power decrease after rod drop with time

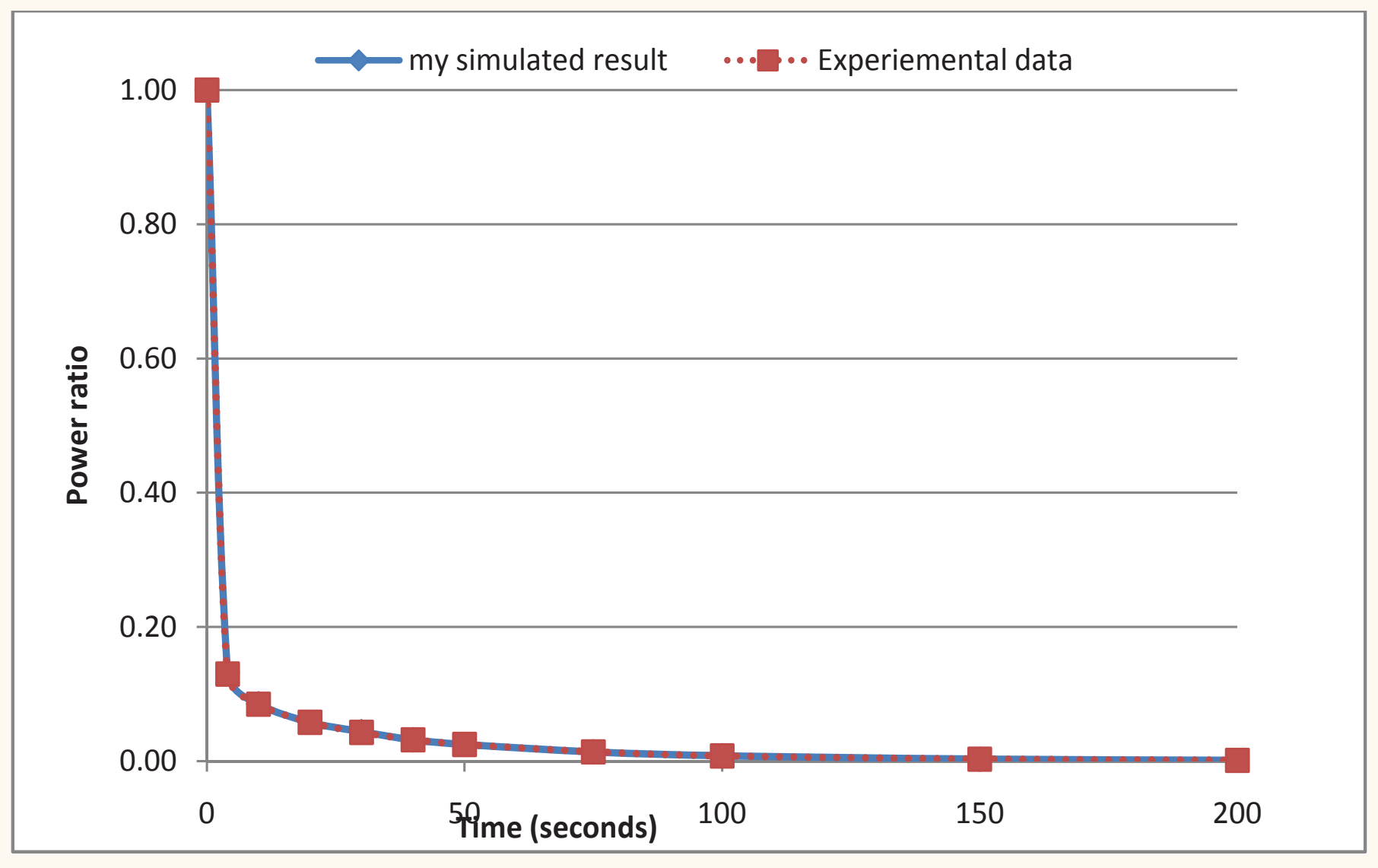


Figure 7: Reactor power decrease with time Power decrease first with a prompt drop then with an exponential decrease with a long stable period.

Rod drop method reactivity of 2.40% for Rod A was obtained that is in range with historical data

Conclusion

The results obtained were comparable to historical data; however other studies suggest that inclusion of temperature effects on reactivity gives a more realistic model of the reactor.

The **"Approach to Critical''** Experiment Simulation model for the CONSORT reactor was successfully developed and with the results obtained, future students will be able to attain a real feel of how to safely control a reactor.

Further modifications may include;
- Power change from low scale meter to high scale meter
- Trips and displays for power meters and Doubling time (period)
- Warnings for pumps and air blast cooler
- Shut Down Amplifiers
- Temperature effects

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