Nuclear Kinetic Model Development for the First Core of a Brazilian Space Microreactor

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Introduction

- The Institute for Advanced Studies (IEAv) undertook the Advanced Fast Reactor Technology (TERRA) project;
- Source of electrical and thermal energy;
- Ensure human survival and operation of essential equipment;
- Designed to provide approximately 1,200 kWth for around 8 years;

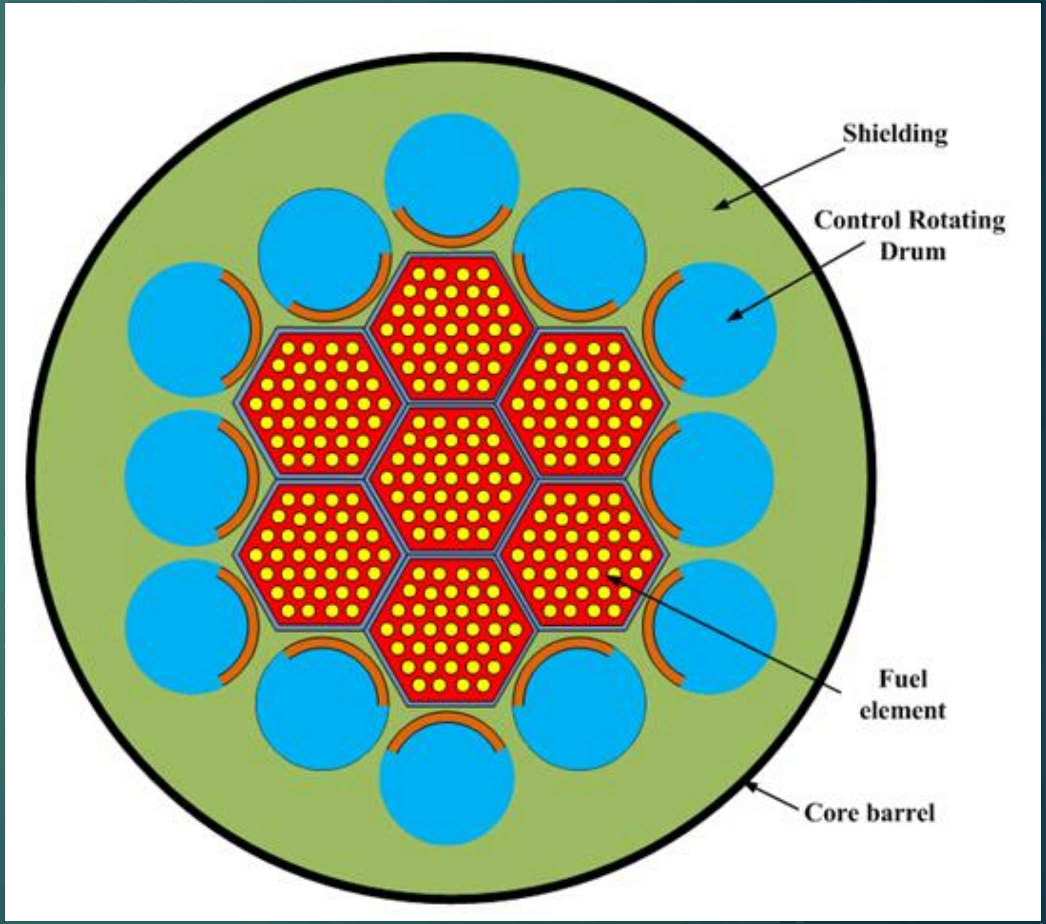
- This paper proposes to discuss the reactor's kinetics, present some kinetic parameters of this core and provide some initial insights of the dynamics of this concept.

Objectives

- Deduce an analytical model of the Point Reactor Kinetics Model coupled with first order thermohydraulics equations;
- Derive the kinetics parameters for TERRA's core;
- Develop a computer program based on MATLAB platform in order to execute the analytical model.

TERRA

- Fuel elements: 10% Pb and 90% UN (enriched up to 82.7% on ^{235}U);
- 37 heat pipes per canister (total of 259);
- Rotating Control Drums: composed of B_4C (absorber) and BeO (reflector);
- Structural material: $Mo_{13}Re$.



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Model Equations

The Point Reactor Kinetics Model

- $\frac{dn}{dt} = \left[\frac{\rho(t)-\beta}{\Lambda}\right] n(t) + \sum_{i-1}^{6} \lambda_i C_i(t)$

- $\frac{dC_i}{dt} = \frac{\beta_i}{\Lambda} n(t) - \lambda_i C_i(t), i = 1, \ldots, 6$

Reactivity Model

$$\rho(t) = rod + c_{kfd} \, log\left(\frac{T_f(t)}{T_{f0}}\right) + c_{kfe}\left(T_f(t) - T_{f0}\right)$$

Energy Balance

$$m_f c_p \frac{dT_f(t)}{dt} = \dot{Q}_c - \dot{Q}_{t+r}$$

where:

$$\dot{Q}_c = k_{cp} n(t)$$

$$\dot{Q}_{t+r} = c_{khf}\left(T_f - T_e\right)$$

Control Method

- Maintain core's power levels in desired interval;
- Guarantee safety and predictability;
- Proportional-Integral (PI) controller:

$$rod = prod + irod$$

$$prod = kgr(pow - n(t))$$

$$\frac{d}{dt}(irod) = \frac{kgr(pow - n(t))}{tir}$$

$prod$ -> signal proportional to power error;
$irod$ -> signal of the integral from power error;
pow -> controller's reference power value;
kgr -> controller's proportional gain;
tir -> integral controller's time gain.

Parameters obtained

- $c_p = 243.1362\left(\frac{J}{kg.K}\right)$ (base temperature of 1000 K [6]);
- $m_f = 192.6\ kg$ [4];
- Considering $k_{cp} = 1{,}200\ kW$, $n(t) = 1$, $T_e = 3\ K$ and $T_f = 1400\ K$ [4] -> $c_{khf} = 858.9835\left(\frac{W}{K}\right)$;

Groups	Λ_i [s^{-1}]	β_i
1	$1.249\ 10^{-2}$	$5.282\ 10^{-4}$
2	$3.182\ 10^{-2}$	$2.749\ 10^{-3}$
3	$1.094\ 10^{-1}$	$2.665\ 10^{-3}$
4	$3.170\ 10^{-1}$	$7.594\ 10^{-3}$
5	$1.354\ 10^{0}$	$2.206\ 10^{-3}$
6	$8.636\ 10^{0}$	$7.798\ 10^{-4}$

λ_i and β_i values for the six groups of delayed neutrons (ENDF/B-VII);

Reactivity coefficients are generic data for fast reactors [7].

Coefficient	Value	Unit
c_{kfd}	$-1.200\ 10^{-6}$	Adimensional
c_{kfe}	$-7.600\ 10^{-6}$	°C^{-1}
rod	0	Adimensional

- $\Lambda = 8.2800x10^{-8}\ s.$

Inserting the model

- All 7 Point Reactor Kinetics Model equations, the energy balance and controller equations were written in the form: $\frac{dy(t)}{dt} = Ay(t) + \vec{b}$

$$A = \begin{bmatrix} \frac{\rho-\beta}{\Lambda} & \lambda_1 & \lambda_2 & \lambda_3 & \lambda_4 & \lambda_5 & \lambda_6 & 0 & 0 \\ \frac{\beta_1}{\Lambda} & -\lambda_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{\beta_2}{\Lambda} & 0 & -\lambda_2 & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{\beta_3}{\Lambda} & 0 & 0 & -\lambda_3 & 0 & 0 & 0 & 0 & 0 \\ \frac{\beta_4}{\Lambda} & 0 & 0 & 0 & -\lambda_4 & 0 & 0 & 0 & 0 \\ \frac{\beta_5}{\Lambda} & 0 & 0 & 0 & 0 & -\lambda_5 & 0 & 0 & 0 \\ \frac{\beta_6}{\Lambda} & 0 & 0 & 0 & 0 & 0 & -\lambda_6 & 0 & 0 \\ \frac{k_{cp}}{c_p m_f} & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{c_{khf}}{c_p m_f} & 0 \\ -\frac{kgr}{tir} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

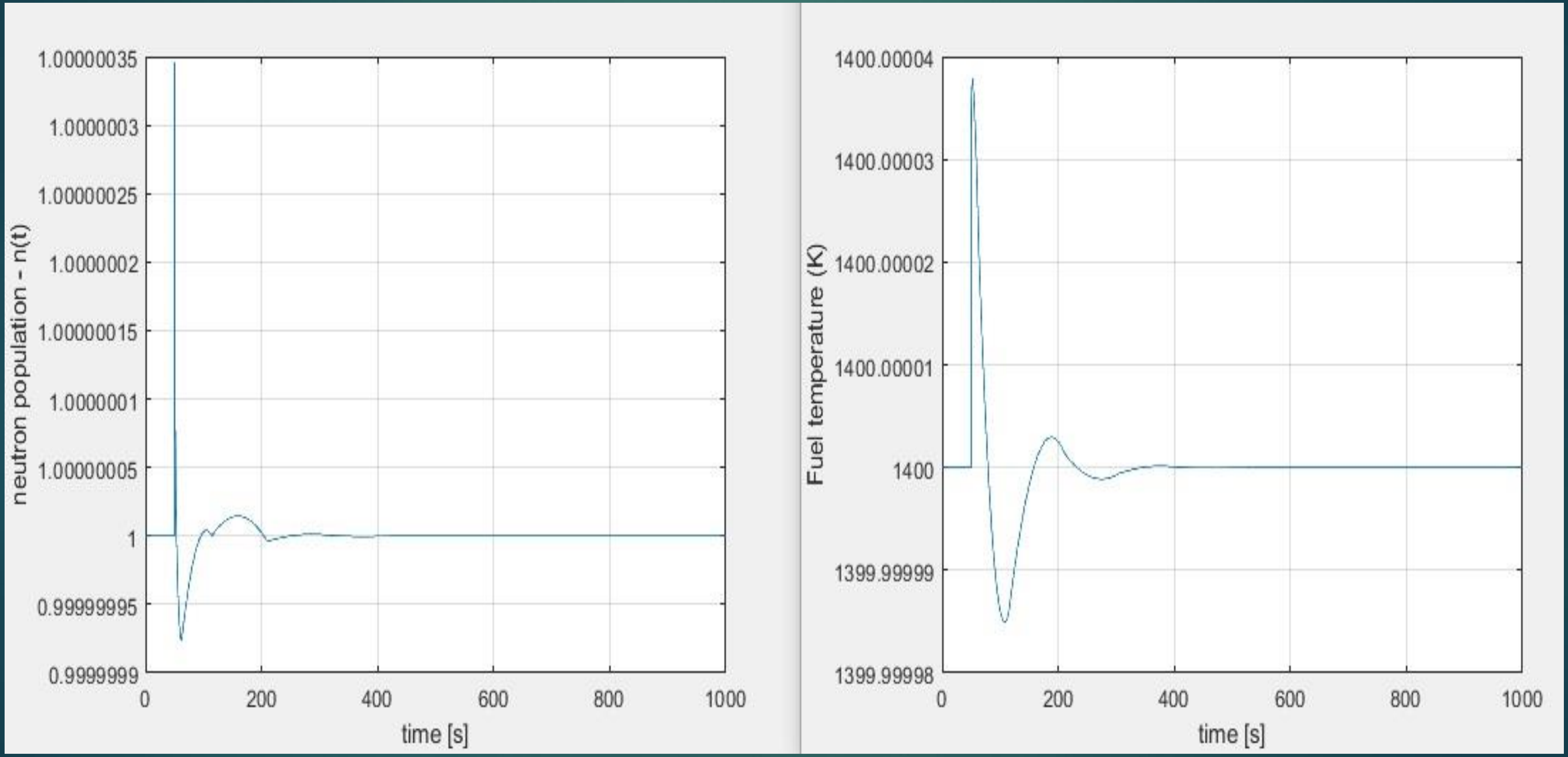
$$\vec{b} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \frac{c_{khf}.T_e}{c_p m_f} \\ \frac{kgr.pow}{tir} \end{bmatrix}$$

Running the model

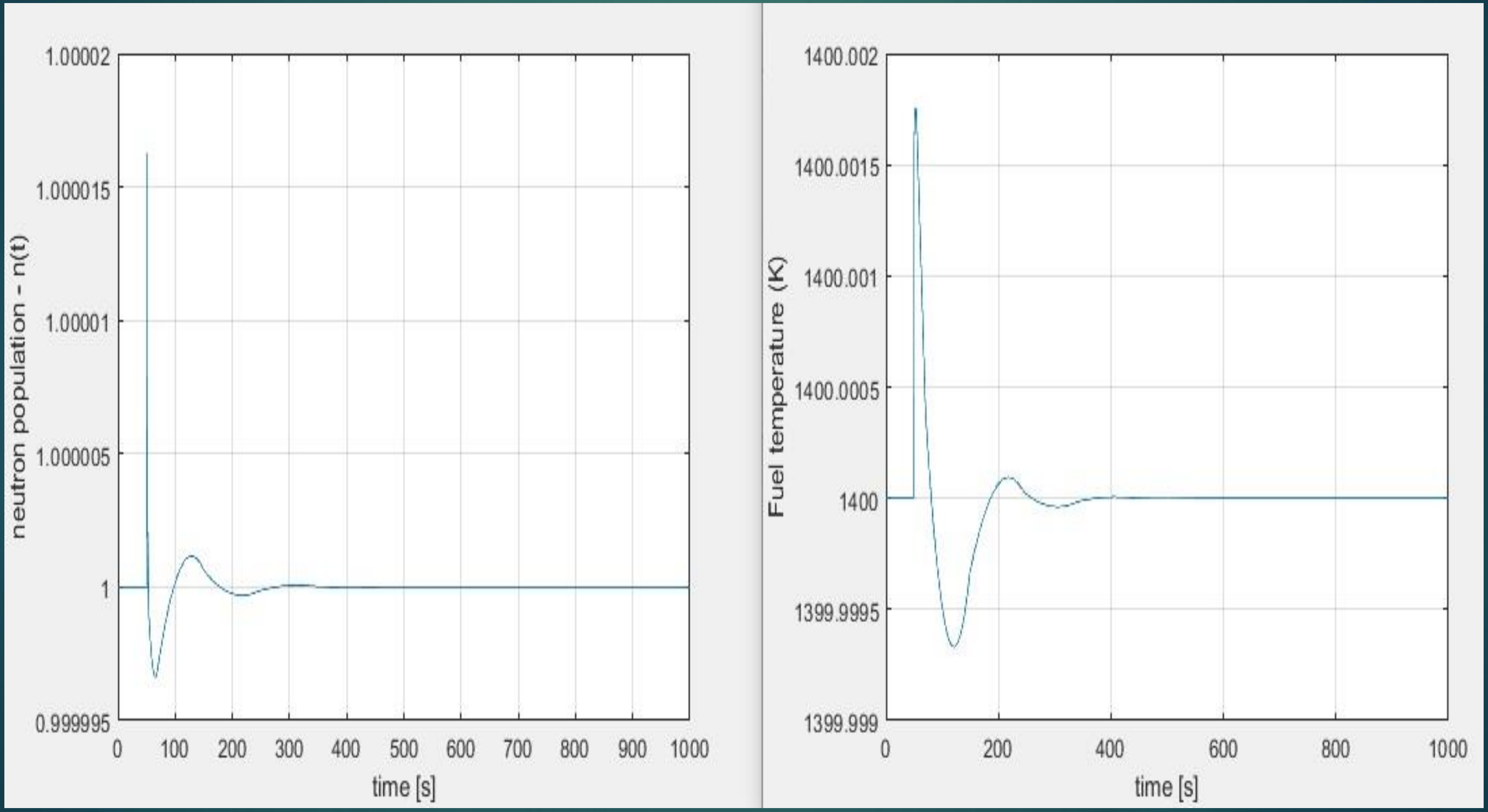
- The set of 9 equations was solved by “ode23s” function in MATLAB;
- In order to test the kinetic micro core model, five types of external reactivity insertions were established at 50 seconds:

1. A small impulse reactivity insertion of \$0.01;
2. A larger impulse but still sub pronto critical reactivity insertion of \$0.40;
3. A pronto critical reactivity insertion of \$1.00;
4. A super pronto critical reactivity insertion of \$1.15;
5. An external reactivity ramp with behavior defined by $\frac{0.1\beta t}{20} - \frac{0.5\beta}{2}$ and ending at 70 seconds, remaining with its final value (\$0.10) afterwards.

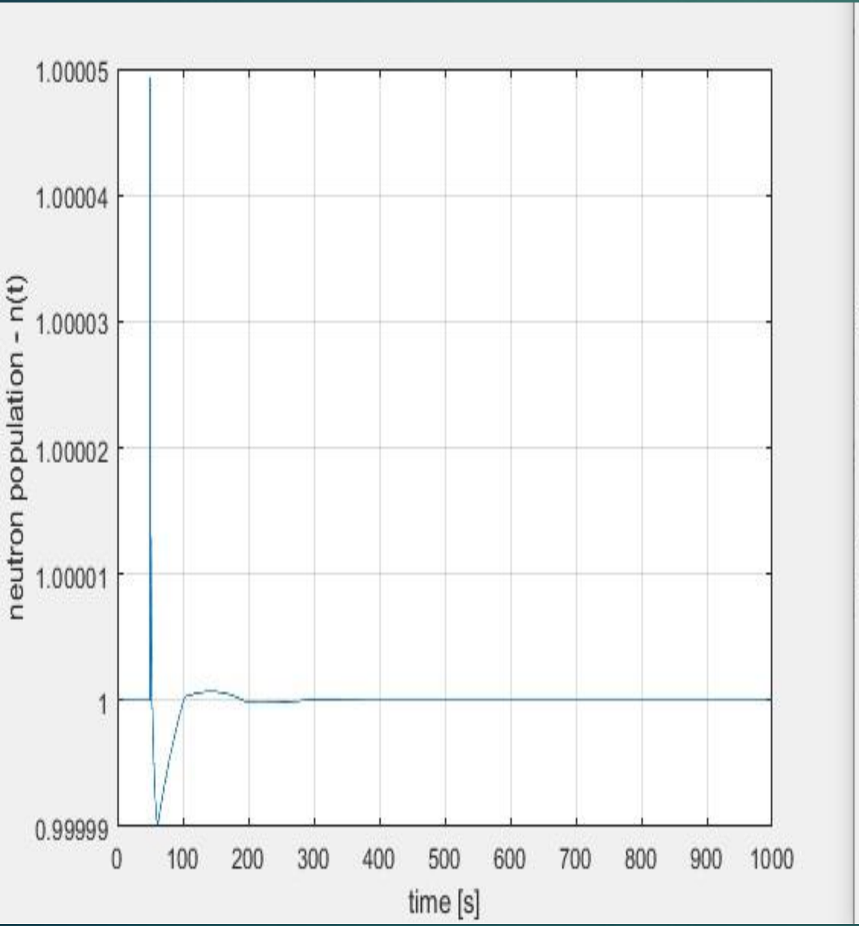
$n(t)$ and $T_f(t)$ behavior with a $0.01 impulse

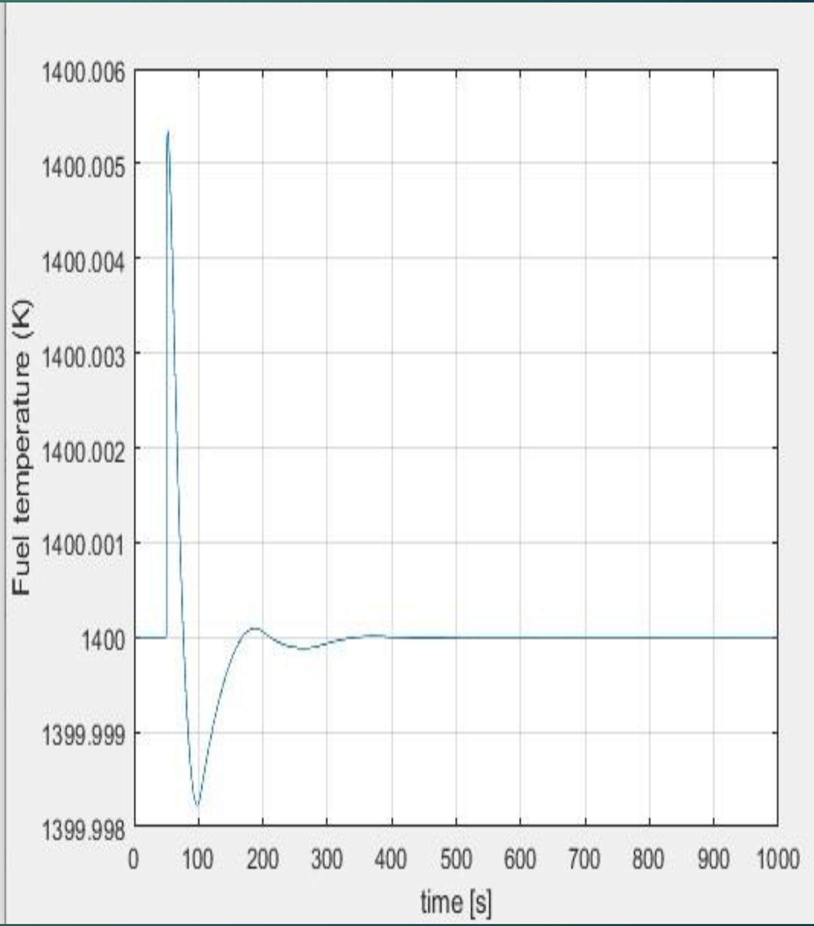


n(t) and $T_f(t)$ behavior with a $0.40 impulse

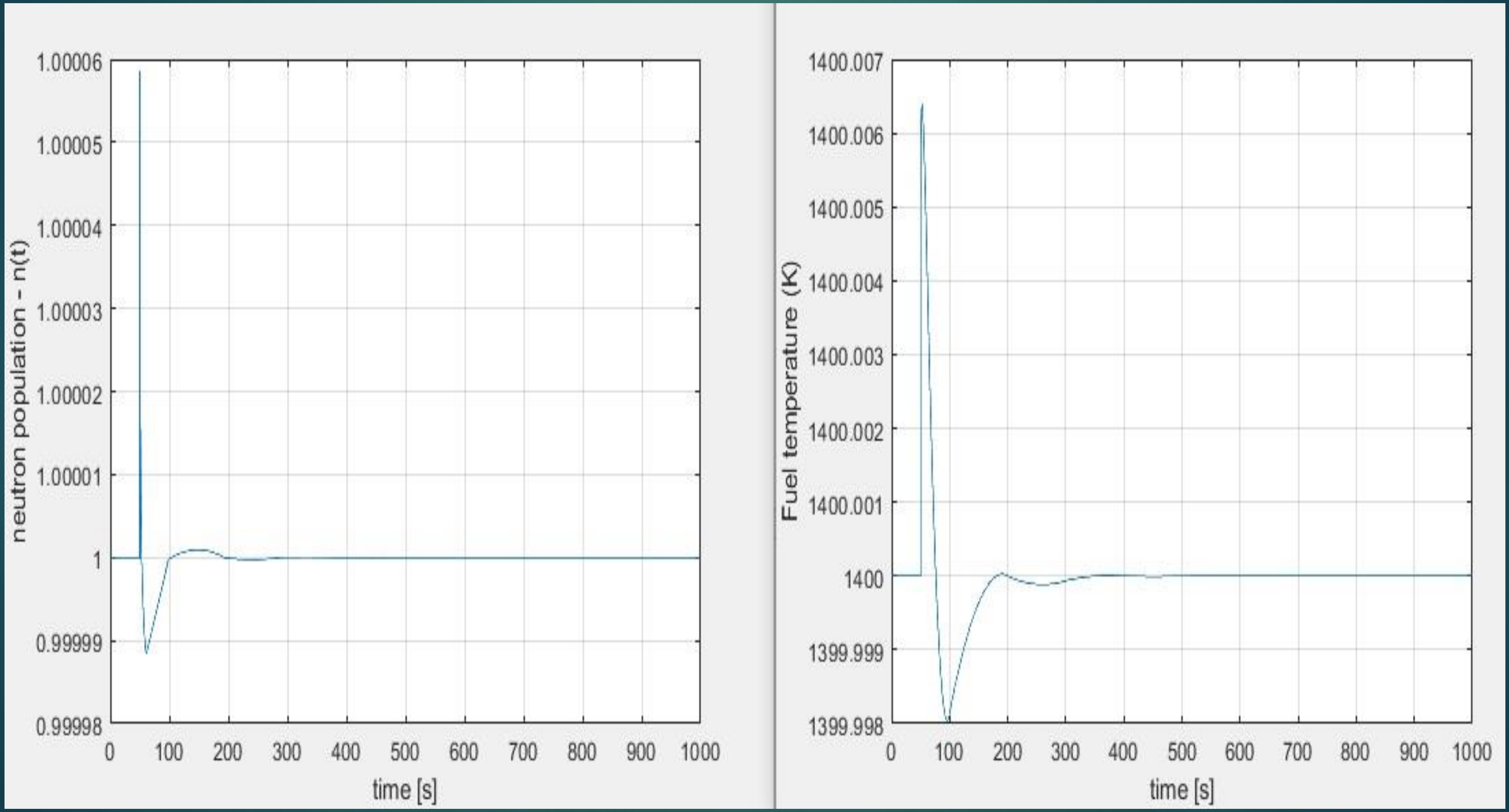


$n(t)$ and $T_f(t)$ behavior with a $1.00 impulse

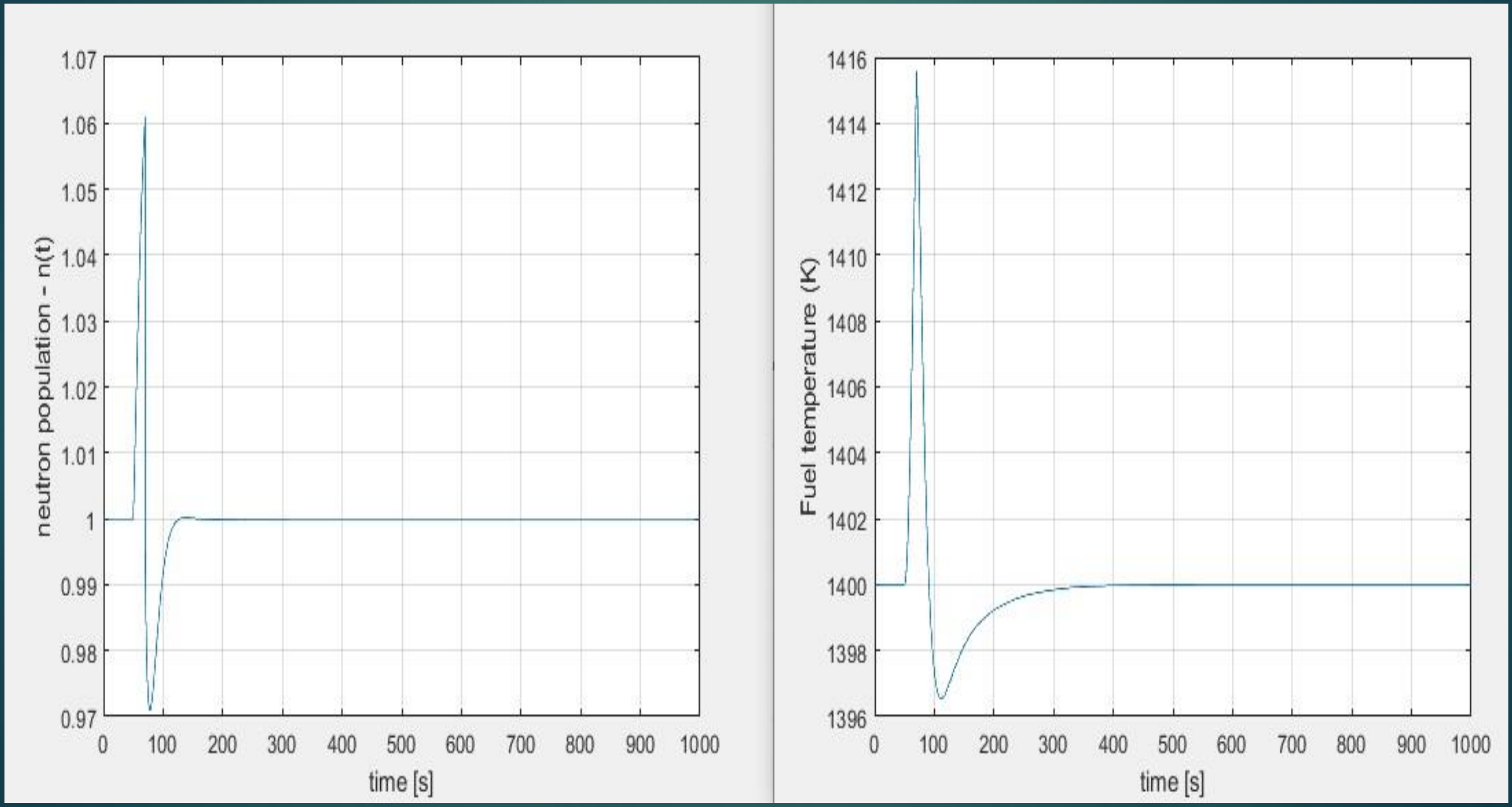




n(t) and $T_f(t)$ behavior with a $1.15 impulse



n(t) and $T_f(t)$ behavior with a $\frac{0.1\beta t}{20} - \frac{0.5\beta}{2}$ ramp ending at 70 seconds.



Results Analysis

- In all values of reactivity insertions, the core rapidly compensated and returned to its original operation level;
  - This is only possible due to the control system;
  - The nuclear power and fuel temperature did not reach any unreasonable values throughout the entire transitory process.

- When ramp insertion was applied, it rose up to 10% of the total fraction of delayed neutrons, β;
  - Response indicated that the microreactor core has enough feedback to absorb this excess.

- Further investigations are certainly required:
  - The feedback considers only two effects, the Doppler broadening and fuel temperature variation effect;
  - The cooling temperature effect has not been considered, as there is no cooling per se, and heat removal is performed by heat pipes;
  - The next steps planned in project TERRA are to further detail the heat pipe effect as well as to improve the energy balance consideration.

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