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"Object-Oriented Modeling and simulation of a TRIGA reactor plant with Dymola"

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Abstract

This work presents the modeling and simulation of a TRIGA-Mark II pool-type reactor with Zirchonium-Hydryde and Uranium fuel immersed in light water, with Modelica object-oriented language, in Dymola simulation environment. The model encompasses the integrated plant system including the reactor pool and cooling circuits.
The reactor pool plays a fundamental role in the system dynamics, through a thermal feedback effect on the reactor core neutronics. The pool model is tested against three experimental transients: simulation results are in good accordance with experimental data and provide useful information about the inertial effect of the water inventory on the reactor cooling.

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Keywords: Reactor dynamics; reactor pool; object-oriented simulation; Modelica; TRIGA

1. Introduction

Nowadays, validated and well-recognized tools for numerical simulation of accident transient behavior in reactor plants are available. On the other hand, control-oriented simulation models have to feature, at the same time, a good level of accuracy and the capability to represent a wide range of operating conditions and transients, at a viable computational effort. In other words, they have to be flexible and robust to a wide change in the input conditions and provide reliable prediction of system dynamics, in reasonable computational time. The Modelica language [1,2] offers an object-oriented approach that makes the modeling of complex systems flexible, modular and re-usable. Components are based on non-linear, first-principles models and are either lumped-parameter models or 1-D

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distributed parameter models. The degree of detail is suited to system studies, while offering acceptable computational time. Modelica language has already been used in the nuclear field [3,4] to simulate the dynamics of an integral-type PWR, in its concept-design phase. This work presents a simplified model of a TRIGA-Mark II (Training Research and Isotope production General Atomics), whose simulation results have been tested against experimental data. A model of the same plant has been presented in [5,6], limitedly to the reactor core, by means of Matlab-Simulink modeling tool, with a causal approach. This model simulated the core dynamics with thermal feedback to the neutronics. The response to reactivity insertion transients was coherent with experimental data on the reactor power dynamics.

In this pool-type reactor plant, the pool thermodynamics is of capital importance in the overall system behavior, since it provides a relevant thermal inertia that influences the core neutronics through the fuel temperature, the coolant temperature and density feedback. For this reason, this work extends the scope of simulation to the full plant including the reactor pool and the hydraulic cooling systems, while adopting the object-oriented modeling approach. This work is a first step in the set-up of a control-oriented simulation strategy [7].

An experimental campaign is currently on-going on the TRIGA plant, to record the temperature measurements of the reactor pool and primary circuit, during different power and cooling transients. The accuracy of the simulation model presented in this work has been validated against these experimental data.

Nomenclature

α_f	reactivity change per fuel temperature change, pcm•K^{-1}
α_m	reactivity change per coolant temperature change, pcm•K^{-1}
α_d	reactivity change per coolant density change, pcm•m^3•kg^{-1}
CFD	Computational Fluid Dynamics
PID	Proportional–Integral–Derivative
PWR	Pressurized Water Reactor
RTD	Resistance Temperature Detector
UZrH	Uranium-Zyrconium Hydride

2. The TRIGA plant

The TRIGA-Mark II reactor at the Laboratorio Energia Nucleare Applicata (L.E.N.A.) of the University of Pavia is a research pool-type reactor with nominal power of 250kW, in operations since 1965. The reactor core is placed at 0.6 m from the bottom of an Aluminum-concrete cylindrical pool (6.25 m height; 1.98 m diameter), containing 18.9 m^3 of water. A graphite reflector ring surrounds the core [8].

Neutrons are moderated by the demineralized water contained in the pool and by the fuel itself. The specific composition of the low-enriched (slightly less than 20%) Uranium-Zirconium Hydride (UZrH) fuel, with 8.5% U in weight. has a large prompt negative thermal coefficient of reactivity. This means that, as the temperature of the core increases, the reactivity undergoes a prompt decrease. Due to the particular interaction of thermal neutrons with the Hydrogen in the fuel lattice, an increase in fuel temperature is able to increase the chance for low neutrons to be accelerated instead of being slowed during an elastic scattering. As a result, the prompt temperature coefficient of fuel is due for more than 80% to the behavior of Hydrogen in the UZrH lattice and for 20% to the Doppler effect and the fuel thermal expansion. Two different fuel element types feature the core configuration: Aluminum clad (Al-1100F alloy) and stainless steel clad (304-SS alloy). Ninety slots are placed in the core in six concentric rings, with 83 fuel elements and 3 control rods - named SHIM, Regulating (REG) and Transient (TRANS) (Fig.1).

The hydraulic system of the TRIGA-Mark II at L.E.N.A. is made up of three separate circuits interfaced with each other: the primary (I), the secondary (II) and the tertiary circuits (III) respectively. An active heat removal system draws the water from the top of the reactor pool and sends it to a the primary hydraulic system, where it goes through a shell-and-tube heat exchanger with exchange surface of 30.7 m^2 and is re-injected above the core upper plate. An intermediate closed loop removes the heat through a second, plate-type heat exchanger, with 45 plates and total exchange surface area of 10.3 m^2. This is interfaced with a tertiary open cooling line [9], that draws coolant from the water main at about 15°C. The mass flow rate in the three cooling lops are in the range of 7 kg/s, 10 kg/s and 7.6 kg/s in the primary, secondary and tertiary respectively, as recorded during the experimental campaign currently on-going (March 15, 2016 – May 2016).

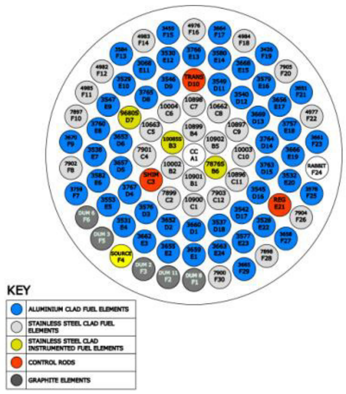


Fig.1 TRIGA core current configuration

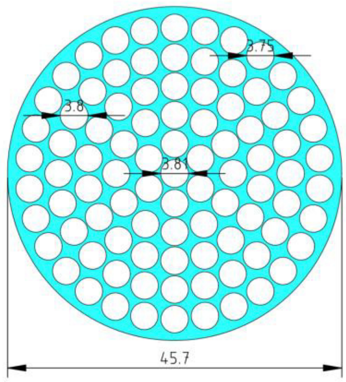


Fig. 2 Core section along the active length: the space between core elements is filled by water, represented in cyan; length is given in cm

Figure 4 shows a sketch of the reactor cooling systems with the position of sensors/meters installed. Sensor TT1 is a RTD PT100 that measures the temperature in the reactor pool [10].

The coolant temperature gradient between core inlet and outlet sections generates a buoyancy force, which drives the fluid upward through the reactor core. When the driving pressure due to the buoyancy force equals the pressure drop, an equilibrium mass flow rate is established. At 250 KW the natural circulation mass flow rate across the core is estimated at 9.3 kg s^{-1} [5].

3. The TRIGA plant model

The model of the TRIGA plant has been built using component models from two different Modelica libraries: ThermoPower and Nukomp. The ThermoPower library [11,12] is open-source [13] and has been developed for the modeling of thermal power plants at system level. Models are derived from first principle equations whenever possible, e.g. mass, momentum, and energy dynamic balance equations, or from acknowledged empirical correlations.

3.1. Fuel model

In the Nukomp library, the neutronics has been described adopting a point reactor kinetics model, with one energy group and six delayed neutron precursors groups [6]: this approximation consists in grouping together the precursors based on their half-lives. Delayed neutrons are represented by six groups: yields (neutrons per fission) and decay constants (λ, sec^{-1}) are obtained from nonlinear least-squares fitting to experimental measurements. Coefficients specific to the TRIGA reactor have been used in the equation system.

A negative feedback coefficient α_f has been considered for the fuel temperature effect (Doppler). Compared to the scale and to the speed of the α_f feedback, the coolant temperature and density reactivity coefficients α_m and α_d have been considered as second order effects and neglected. Experimental campaign is currently ongoing on the TRIGA plant, to retrieve data (through fast and slower power transients) and calculate the coolant reactivity feedback coefficient.

Control rod total worth (REG) is about 1.1 $ for total insertion (38 cm). In this way, for the purpose of this work, total reactivity ρ (pcm) for a critical system is given by the sum of the fuel temperature effect and the control rod insertion effect:

$$\rho = \rho_f + \rho_{CR} \quad (1)$$

In the model, a PID controller has been introduced to keep the core power at its nominal level of 250 KW during all the simulation transients, as it was done during the experimental test by means of the REG control rod.
The model for the heat generation in the fuel considers the radial heat transfer, neglecting both the axial and the circumferential diffusions. Five zones are identified and modeled: three concentric zones in the fuel pellet with equal volume, the gap and the cladding (Fig.3).

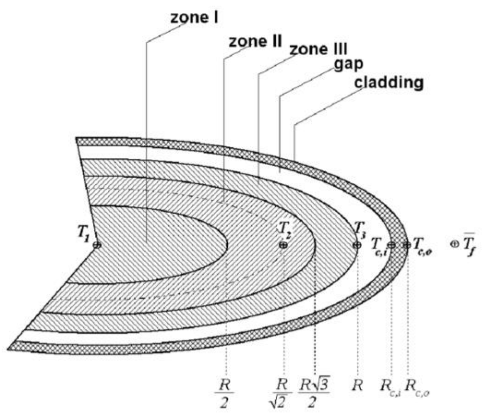


Fig.3 - Scheme of the fuel radial heat transfer modeling

The time-dependent Fourier equation in mono-dimensional cylindrical geometry is applied to each of these zones. The conditions of heat flux vanishing at the pellet center and the continuity of the temperatures and heat fluxes at the three boundaries regions allow the determination of temperatures. Fuel rods are modeled into seven longitudinal segments. As a result, the model calculates 35 variables (temperatures) of the fuel. Average fuel rod temperature for the Doppler feedback computation (T_{eff}) is calculated as follows:

$T_{eff} = 4/9T_{r=0} + 5/9T_{r=R}$

where r=0 and r=R are the center and the boundary of the fuel rod respectively. Aluminum properties are assumed as representative of all the fuel elements cladding.

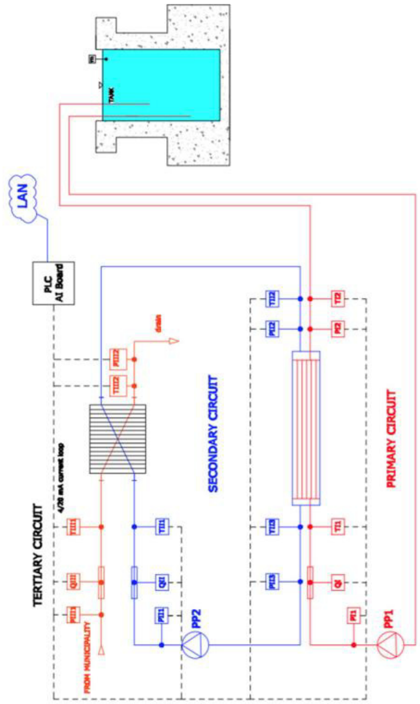
Inside the core model, a 1-D tube model for water/steam flow is used, to represent the coolant thermohydraulics, with a turbulent friction model for the pressure drop calculation. This pipe has 35.6 cm length (as the active length of the Aluminum fuel rods), heated perimeter of 9.8 m (as the total perimeter of all the fuel channels) and a cross section equal to the difference among the total core area and all the fuel channels (Fig.2). The mass, momentum and energy balance equation are discretized with the finite volume method. The state variables are: one pressure, one flow-rate (optional) and N-1 specific enthalpies.

Distributed heat transfer model with constant coefficient is assumed at the interface with the fluid. The heat transfer coefficient depends on the coolant mass flow rate condition as well as on core geometry and it can be estimated using the Dittus-Boelter correlation, valid for turbulent flow in narrow channels.

Two additional tube model components of 18.3 cm length are placed on top and bottom of the core, to account for the core total length (72 cm), besides the active zone. These two components have the same geometry as the core tube model in terms of hydraulic diameter, cross section and heated perimeter. Nominal Fanning friction factors have been appropriately set in the natural circulation loop, to comply with the estimated mass flow rate:

3.2. Thermohydraulics

Finite Elements Models (FEM) 1-D distributed-parameter for water/steam flow in a tube, have been used to build the hydraulics circuits, one-phase, with mass, momentum and energy balance partial differential equations. Weak formulation of governing differential equations, as allowed by FEM numerical method, has been assumed, reducing the continuity requirements on the solution and facilitating the steady state initialization of the model simulation. Heat dispersion along the circuits has not been considered; heat transfer is concentrated in the two heat exchangers. Heat exchangers A and B have been modeled as concentric tube-type, by interfacing Finite Elements Models (FEM) 1-dimensional distributed-parameter for water/steam flow, with a metallic walls component (Fig.5). Each 1-D tube flow model represents the primary or secondary side of a heat exchanger. The thermal exchange area is the same as in the original heat exchangers; the metal walls component is equivalent to the overall surface of the tube bundle between the primary and secondary side of the mass flow, with stainless steel properties. A constant heat transfer coefficient has been assumed for the heat transfer model.



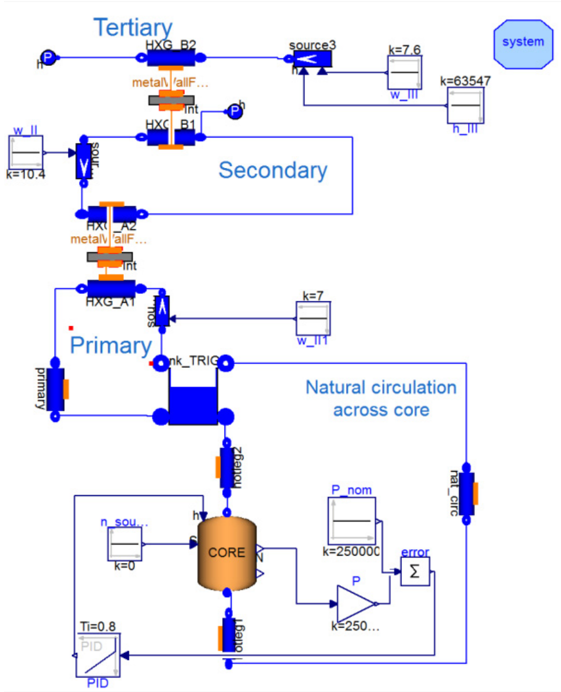


Fig.4 – Scheme of the TRIGA plant and hydraulic systems Fig.5 – Scheme of the TRIGA model in Dymola

A higher heat transfer coefficient has been assumed for the heat exchanger in the secondary-to-tertiary side, to account for higher compactness of the plate-type component respect to the shell-and-tubes type; in the modeling of this component, the number of tubes has been assumed equal to the original number of plates (i.e. 45). Key data of the heat exchanger models are summarized in Tab.1.

Tab.1 - Technical data of the two heat exchangers (A and B)

	A1-primary	A2-secondary	B1-primary	B2-secondary
Num. tubes	129		45	
Length (m)	4.2		4	
Exchange surface (m^2)	30.7		10.3	
External/internal Surface ratio	3.5		3.5	

An *ad hoc* model component for the reactor pool has been set up starting from a standard Thermopower tank model, by featuring additional inlet and outlet ports on the top of the component volume. Two hydraulic circuits are connected to the pool through 2 inlet and 2 outlet ports: the natural circulation virtual loop, that is set up between the core and the pool water inventory and the primary cooling loop, that draws water from the top of the pool and re-injects it at the bottom of the pool. The natural circulation water flow that comes out of the core, enters in the pool where it get mixed with the cool water mass flow from the primary heat exchanger and flows again into the bottom of the core. Elevation of outlet over inlet is equal to the height of the water column above the core (i.e. 5.54 m). The natural circulation virtual loop is closed by a down-flow 1-D tube model with 6.25 m length and 0.6 m diameter: this gives a volume of approximately 1.8 m^3, that is an assumption on the water volume actually involved in the natural circulation phenomenon (i.e. about 10%, out of total reactor pool water content). This volume added to the water inventory in the pool model gives the 18.9 m3 water inventory contained in the original reactor pool. Natural circulation is driven by the difference in the hydrostatic pressure between top and bottom of the reactor core, that creates a buoyancy force; when this force is equal to the pressure drop in the virtual natural circulation loop, a steady state mass flow rate is set up in the circuit. The Dymola solver calculates the state system balance equations associated to the model and finds the solution to the natural circulation mass flow rate.

Finally, some mass-through components from the Thermopower library have been used to drive forced circulation in the three cooling loops; these components, together with pressure sinks, allow to avoid the use of pumps in the simulation model and related numerical instabilities, for the sake of simplification and computational burden reduction.

4. Experimental settings and results

Three experimental transients have been performed on the TRIGA plant of Pavia, whose measurement data are used for the validation of the reactor pool simulation model. The reactor is brought at its nominal power and kept at 250 KW during the entire experiment; each time, the cooling systems are activated at a different threshold temperature of the primary circuit. Primary circuit temperature is measured by a PT100 at the heat exchanger inlet and recorded.

The first transient had a duration of two hours and the cooling system is started when temperature in the primary circuit reaches 31°C. Primary and secondary circuits have been started simultaneously 6' after the activation of the tertiary circuit.

The second transient had a duration of 6 hours at nominal power (250 KW) and the trigger value of the primary temperature for the starting of the cooling system was set to 25°C.

The third transient had a duration of three hours with cooling system started when primary water temperature reached 35°C.

The model inherits some uncertainty on the mass flow rate in the three cooling circuits, since uncertainity in the flow rate measurement by the electro-magnetic and ultrasonic meters can be estimated in +/- 10%and the cooling start-up ramp in the experimental conditions is not known.

In the first transient, the experimental and simulated primary temperature profiles have the same cooling rate when cooling systems are active (period 3720-7320 s): +2.4°C•h^{-1} temperature increase is calculated for both experimental and simulated transients. Figure 6 shows experimental and simulation results of the first transient. Temperature measurements are taken via IEC 60751 Class A RTDs; uncertainty can be estimated in 0.4° C including transmitter accuracy and long-term stability effects.

Results of the second and third transient are shown in Fig.7 and 8 respectively.

Long-term simulation of transients 1, 2 and 3 (Fig.9), shows that, beyond the initial ramp shape, that depends on the thermal history - i.e. the activation time of the cooling system - the primary temperature reaches the steady state value of 39.7 °C in all of the three experiments, far from the 41°C maximum design value.

Figures 10-12 show selected state variable dynamics simulated on a long term time period (400,000 s). Figure 10 shows enthalpies at the inlets/outlets of the reactor pool:

- water flow coming from the core (inlet 1) and coming back from it (inlet 2);
- water enthalpy at outlet 1 and 2 - to the heat exchanger and to the core respectively - that represents the mixed water inventory in the pool and therefore have the same value.

Figure 11 shows that, after the ramp-up of the cooling systems, the natural circulation mass flow rate stabilizes at a steady state value of 9.3 kg•s^{-1} at 250 KW power level, in accordance with [5], driven by the coolant density difference across the core (Fig.12).

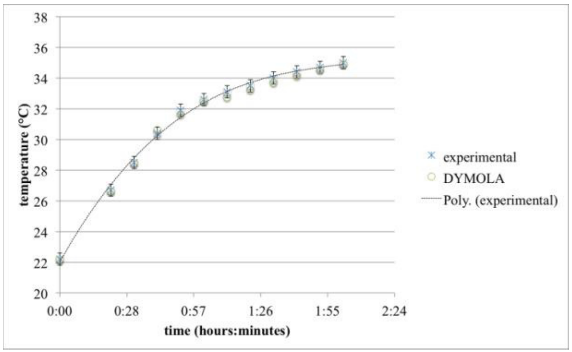


Fig.6 – First transient: simulation and experimental results

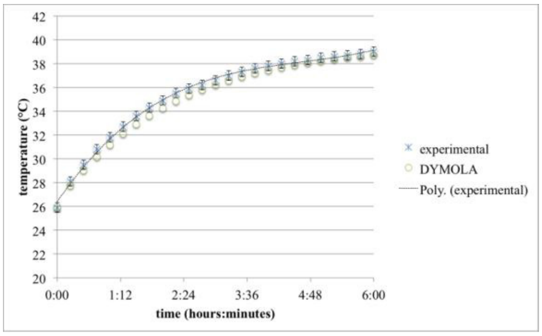


Fig.7 – Second transient: simulation and experimental results

Tab.2 - Second transient. Calculation of cooling rates over two time periods

Period	Experimental T increase	Simulated T increase
s 0-10800	10.7 °C/1h	10.3 °C/1h
s 11700-21600	2.0 °C/1h	2.1 °C/1h

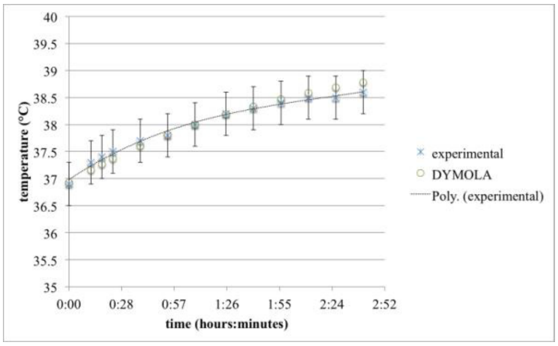


Fig.8 – Third transient: simulation and experimental results

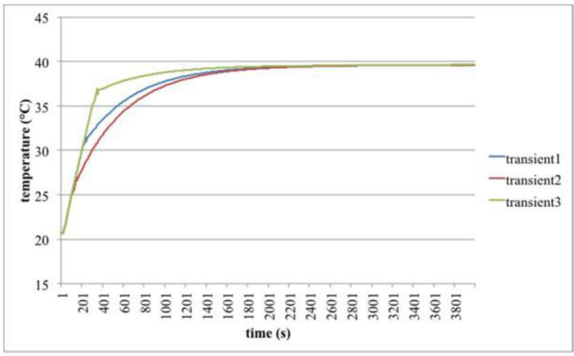


Fig.9 – Long term transient simulation: temperature dynamics of primary circuit

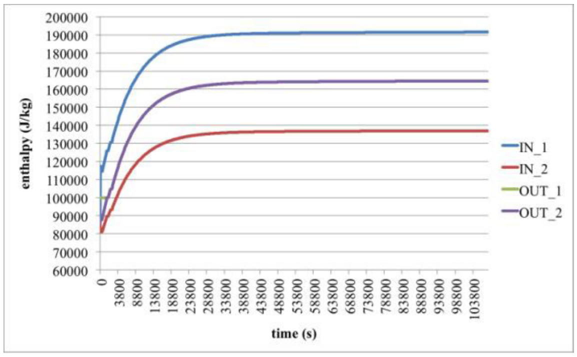


Fig.10 – Water enthalpies at the inlets and outlets of the pool: inlet 1 from core, inlet 2 from primary cooling loop, outlet 1 and 2 are superposed

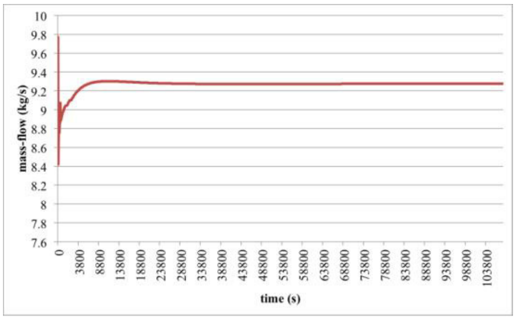


Fig.11 –Natural circulation of coolant across the core

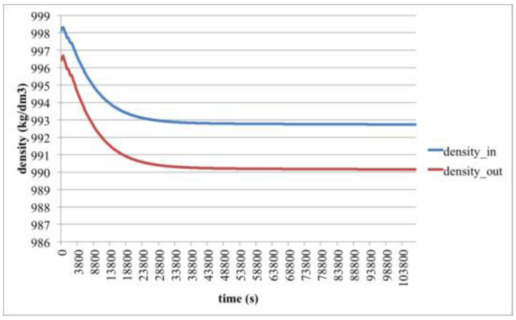


Fig.12 – Coolant density difference across the core

5. Conclusion and future work

This work demonstrates that the a-causal object-oriented modeling is a flexible tool to build a reactor plant simulation model. The plant modeling is flexible in up-grading or expanding the simulation model; the computational burden is limited compared to the full 3-D modeling tools, in a way that a full set of state-space variables simulation values are available in a suitable time. Dymola lumped-sum / 1-D distributed model proves to be a reliable tool since simulation results are in good accordance with experimental values. Assumptions and simplifications have been made for modeling purposes, that can affect the simulation accuracy against experimental data record. Despite these approximations, simulation outcome has an acceptable accuracy range, suitable for dynamics and control purposes. It has been proved that the pool thermal inertia is high enough to smooth the reactivity transients and keep adequate reactor core cooling for hours.

The application of 3-D CFD simulation on the TRIGA plant dynamics, with the calculation of the variables on the whole spatial field, may provide useful insights on the natural circulation phenomenon in the reactor pool, pool cooling and mixing effects and their feedback to the core power.

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