# Interactive Graphic Simulator

# of the CAREM-25 Reactor

A tool for design verification and operator training

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**Abstract**

The paper presents the Interactive Graphic Simulator (IGS) of the CAREM-25 reactor, which is used as a tool for verifying its engineering and design. The development of this IGS is part of the design and development of a Full-Scope Simulator (FSS), which will be used for training operators of the CAREM-25 nuclear power plant. The paper describes the models of the systems included in the IGS, along with the graphical user interface, and mentions the tool used for exchanging variables between the different coupled codes involved. The paper also shows the types of simulations that can be performed with this simulator and how they are used to support the reactor design.

## INTRODUCTION

The use of simulators is essential for the training, retraining, and continuous education of operational personnel in a nuclear power plant. With these tools, personnel can efficiently acquire the necessary knowledge, skills, and qualifications to operate the plant, as well as gain operational experience, including dealing with human error.

The first computerized simulators replicating control rooms began to be used in the 1970s. Until then, the scope and fidelity of plant process models were significantly limited due to the restrictions of computational capabilities, and only few facilities had such training tools. However, their expansion and extended use for training in the nuclear industry did not occur until the 1980s, mainly motivated by the events at Three Mile Island in 1979 and, even more so, after the Chernobyl accident in 1986. These incidents led to significant improvements in plant personnel training programs, especially for control room staff. These changes were driven by lessons learned from operational experience, resulting in enhancements to simulators used as training tools. Before these accidents, installed simulators had numerous deficiencies, primarily in their mathematical models, which did not adequately represent plant phenomenology under certain conditions, and in the design and layout of control room panels [1]. They were non-specific tools often used to train operators of various types of nuclear power plants.

Currently, simulators used for operator training consist of three main parts: the Human-System Interface (HSI), which emulates the plant's Supervisory Control and Data Acquisition (SCADA) system; mathematical models that represent the dynamic behavior of the plant's physical systems; and the instructor's console, from which the simulation is commanded, faults are introduced, and/or field actions are implemented. Since plant operators must monitor and supervise variables and alarms of the main plant systems (reactor core, cooling systems, process systems, reactor protection systems, etc.) through control room consoles and panels, it is essential for the simulator to include the same signals connected to the plant's SCADA system, along with those associated with field actions. Thus, the scope of the simulator models must allow reproducing the same actions as in the actual plant for operating the reactor under both normal and emergency conditions (sometimes even beyond the design basis). Therefore, the simulator must be capable of simulating plant dynamics so that the operator can make real-time decisions when an event occurs.

In the Process Control Department of the National Atomic Energy Commission (CNEA), a simulator for the CAREM-25 reactor [2][3] is being developed. This simulator will be used to support the training of personnel, especially control room operators. In particular, this simulator will have the following characteristics:

**Full Scope:** The mathematical models are detailed enough to represent the same set of variables in the simulator control room as in the reactor control room.

**Training-Oriented:** Real-time simulations are performed to provide proper operator training, respecting the evolution and trend of events and critical variables as they would occur in the actual plant.

**Plant-Specific:** The mathematical models used represent the phenomenology and processes corresponding to the CAREM-25 reactor.

**Full Replica:** The simulator's control room is an exact replica of the reactor's control room, representing all consoles, buttons, and switches the reactor's control room will have. The control system is emulated through a simulator provided by the control system manufacturer that contains exactly the same control logics.

During the development of this simulator, there has been a need to use early versions to support the engineering design of the reactor. These versions differ in the scope of the mathematical models, the graphical user interface, and the objective for which they will be used. Thus, a new development line emerged for the simulator, which is used for verifications through the use of engineering models. For this simulator, the objective is not the training of operators, but analyzing the plant's or system's response under certain operational conditions and operator actions.

## ENGINEERING VERIFICATION simulator

To develop the mathematical models for a simulator that will be used for personnel training, it is necessary to have the basic engineering of the systems to be modeled. Due to the state of engineering progress of the plant systems, and given the complexity associated with the operation of the entire plant, there have been requirements for the simulator development team to obtain specific models or versions of the simulator in order to conduct several types of analyses to evaluate and verify, through simulations, the interactions of the systems included in the simulator. Thus, different versions of the engineering verification simulator have emerged, differing essentially in their use and type of analysis, and consequently in the models and graphical interface they possess.

SimFase1 [4] is an interactive graphical simulator (IGS) for the CAREM-25 reactor. This IGS is used as a tool to carry out various analyses during the design stage of the main process systems, allowing a qualified user to perform simulations of operational maneuvers for the transition between different operational states and design basis events (DBE). Its main objective is to verify the basic design of operational maneuvers, the main control loops, and the trip limits of the reactor's safety systems. Additionally, it allows for the study and analysis of the effect of the main reactor regulations in the event of the following DBEs[[2]](#footnote-3):

Anticipated Operational Events:

* Turbine trip
* Reactor trip
* Feedwater increase
* Feedwater temperature decrease
* Main steam isolation valve closure
* Loss of external power supply

Postulated Design Basis Accidents:

* Reactivity insertion
* Loss of coolant event in the vapor zone of the reactor pressure vessel (RPV) dome
* Loss of coolant event in the liquid zone of the RPV dome
* Feedwater line break
* Main steam line break

There is another version of SimFase1 that will also be used to connect to the plant control system emulator provided by Siemens [5]. The control system emulator emulates the logic that will be implemented in the PLCs and uses the same programming software as the control system itself. In this way, by interconnecting the simulators, the programmed control logic for the different processes can be evaluated, and the performance of the control system under various operating conditions can be analyzed in simulation.

This version constitutes an initial phase of the full-scope simulator since it includes the mathematical models that will be used by the training simulator. It also features an ad hoc user interface that allows user interaction with the models during the simulation and lacks an instructor console as it is a preliminary version whose scope does not include personnel training.

## MODELED SYSTEMS

The SimFase1 simulator models the primary system, secondary system, main reactor controls, purification and volume control system, shutdown cooling system, control rod drive mechanisms (MSAC and MSER), reactor protection systems, and safety systems, which include the first shutdown system (FSS), safety injection system (SIS), and residual heat removal safety system (RHRSS). It also includes a dynamic Xenon model that accounts for reactivity changes due to power variations and a point kinetics model with feedback coefficients to represent the reactor's neutronic behavior. There is also a neutron model of spatial kinetics, the PUMITA for CAREM-25, which can be used to analyze certain transients [6].

The simulator runs on a platform developed in Matlab/Simulink [7] and allows connection with external codes such as RELAP5 [8][9] through the relapService [10], which enables the exchange of variables between different codes.

The SimFase1 includes a graphical interface with panels that facilitate user interaction with the reactor models during a simulation. The interface allows modifying valve openings, inserting reactivities, turning systems on and off, and changing controller setpoints, among other actions. It also includes a panel for inhibiting the safety system trip parameters and panels for performing heating and cooling maneuvers. Additionally, the interface provides the ability to select reactor control modes, which involve different controller configurations.

### Primary system

The primary system model of SimFase1 consists of the model used for accident analysis, programmed in RELAP5 and described in detail in the CAREM-25 Project documentation [11]. A set of modifications was implemented to adapt it to the platform used to run the simulator and to the operating conditions that are of interest to represent.

The primary system model incorporates models of the dome, chimney, steam generators, and models of the downcomer, lower plenum, and core in the lower part of the reactor pressure vessel. Additionally, it includes a model for the first shutdown system (associated with the neutronic model) and for the residual heat removal safety system and the safety injection system.

The model includes the steam condensation power in the dome due to the structures of the systems located in that area.

### Secondary system

The secondary system was modeled by using the RELAP5 plant code and includes both the part of the system within the containment as well as the Balance of Plant (BoP) and the turbogenerator [12]. The system contains the two branches for each group of steam generators (SGs), identifying the feedwater line, the steam line, branches for the startup phase separator, and feedwater to preheaters.

The model includes the startup phase separator, which is relevant for performing the reactor heating and cooling maneuvers. Additionally, it represents the main steam isolation valves (MSIV), main steam safety valves (MSSV), controlled relief valves (CRV), turbine control valves (TCV), turbine bypass valves (TBV), feedwater flow control valves (FFCV), preheater valves (PHV), and phase separator discharge valves (PSDV), which are particularly important for performing process, regulation, control, and safety actions.

The model also represents the heating of the feedwater to the steam generators through two preheaters, which receive steam from the main steam linebvx, auxiliary steam, and turbine extraction systems, depending on the state of the reactor.

### Process systems

The process systems integrated into this simulator were modeled using elements from the ModBas thermal-hydraulic component library [13]. This library is an in-house development and has already been used to develop models in other simulators [14]. Thus, the modeled systems are coupled with the RELAP5 models through variable exchange via the simulator platform.

#### Purification and control volume system

The Purification and Volume Control System aims to control the primary level during normal reactor operation and the primary pressure when it is in solid mode during startup. Additionally, it can perform the function of cooling the primary if necessary [15].

#### Shutdown cooling and startup heating system

The Shutdown Cooling and Startup Heating System aims to cool the primary when the reactor is shut down and cooling with the steam generators has ceased. It also performs the function of heating the primary during reactor startup until nuclear power is available [15].

### Reactor protection system

The Reactor Protection System (RPS) model includes the trip logics for the scram, as well as for the Safety Injection System (SIS) and the Residual Heat Removal Safety System (RHRSS). The trip logics were programmed in Simulink, and the values presented were used to compare the trip parameters associated with the different safety systems. Sliding trip limit values (STLV) are defined for various trip limits to adapt them to the different operating conditions of the reactor.

### User interface

The user interface consists of various panels that can be opened and closed from the Simulink model throughout a simulation. These panels allow the user to evaluate process variables and interact with the models during a simulation. Within each panel, there are objects that interact with the Simulink models, which can represent controllers, process variable measurements, process variable manipulation, on/off buttons, or other blocks with specific functions.

Fig. 1 shows the Power Panel. This panel contains measurements of the main process variables, controllers, and special blocks, allowing regulation of live steam pressure (secondary), feedwater temperature to steam generators, primary pressure, turbine power, and reactor power. The Control Mode block allows choosing the reactor control mode: *reactor follows turbine* or *turbine follows ractor*. The Block Power block allows selecting the electrical power reference and the speed at which to change the references in the corresponding controllers.

The OPM-PCA and PCA-OPM buttons open special panels for transitioning between normal operation and hot shutdown states, and vice versa. The panels allow monitoring the evolution and comparing with reference values during the maneuver of interest to relevant transient variables.

The interface also includes an Inhibitions Panel for the signals corresponding to the trip parameters of the safety systems acted upon by the Reactor Protection System. The panel presents the signals that lead to the shutdown grouped according to their origin: nuclear, processes, and others. It also presents the signals associated with the SIS trip and RHRSS trip. Additionally, through Global Inhibitions, each of the 6 signal blockages can be globally inhibited, regardless of whether the signal is individually inhibited or not.

When the signal name is in red, the signal is inhibited, while when it is in green, it is not. When the signal is inhibited, it means that if the signal trip condition occurs, it will remain inactive for the Reactor Protection System. When the signal is not inhibited, it will be considered for the corresponding system trip if the activation condition is met.

Fig. 2 shows the operating modes of the interface controllers. The controllers that allow interaction with the user are part of the panels belonging to the graphical user interface (like those in Fig. 1). For remote setpoint, the controller receives the reference from another block, which can be another controller (Fig. 2 (a)). For local setpoint, the reference is generated in the controller itself and can be changed through the button panel indicated in Fig. 2 (b). For normal mode, the controller does not use remote or local references and allows changing the value of the controlled variable (CV) it acts upon through the button panel in Fig. 2 (c).

When changing from automatic with remote setpoint to automatic with local setpoint, either through user interaction or due to some automation, the local setpoint automatically switches to the current value of the process variable (PV). For the Manual to Automatic mode change, the local reference is used, with the local setpoint being the PV value at the time of the change.

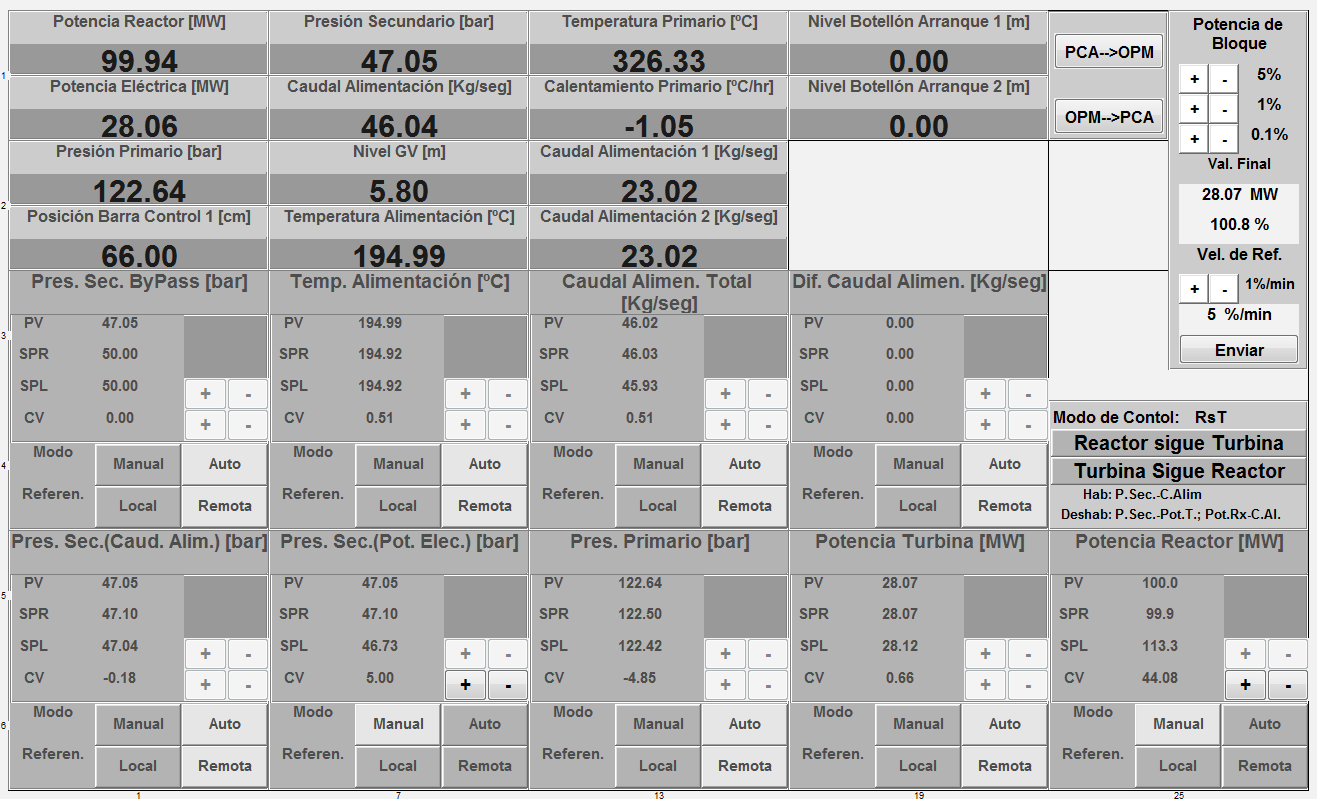


FIG . Power Panel: contains blocks with regulators, process variable measurements and special blocks.

|  |  |  |
| --- | --- | --- |
| autoremoto.png  (a) | autolocal.png  (b) | manual.png  (c) |

FIG 2. Operating modes on the controller interface: (a) Automatic with Remote Setpoint; (b) Automatic with Local Setpoint and enablement to set the reference; (c) Manual and enablement to set the CV value on which the controller acts.

### Operational transients

The IGS is a fundamental tool for the development of the plant's operational maneuvers, such as the reactor startup and shutdown procedures. The startup procedure of the CAREM25 reactor consists of three distinguishable parts: a non-nuclear heating phase, a nuclear startup phase, and operation to full power.

The non-nuclear heating phase involves bringing the plant from a cold shutdown state to a hot standby state, where the primary system and process systems possess the necessary conditions to begin the withdrawal of the absorber elements from the core. These conditions include, among others, maintaining a specific temperature and pressure in the primary system, having steam in the RPV dome and having preheated water for different process systems.

The nuclear startup phase encompasses the procedure by which the absorber elements are gradually withdrawn to achieve core criticality, in order to start generating nuclear power.

Lastly, the operation up to full power consists of increasing the reactor's power until reaching its nominal power. This process is further subdivided into two parts: operation up to minimum power, and then coupling of the turbogenerator and operation up to nominal power.

In the first part, the plant is brought to minimum power operation conditions through an automation that allows synchronized movement of control rod banks and opening of the FFRV. This process takes the plant to the operating state that allows turbogenerator synchronization.

Once this operating state is achieved, the turbogenerator is connected to the live steam line and the plant is brought to its nominal power using the same automation mentioned earlier.

The engineering verification simulator allows qualified users to simulate each segment of the maneuver to study the evolution of the main parameters of the plant, thereby verifying the proper functioning of plant systems throughout the operational transient. The RELAP5 and Matlab/Simulink models enable a qualified developer to access much more detailed information than an operator would have in a real plant, allowing for the plotting and analysis of the temporal evolution of various plant variables and/or the spatial distribution of these variables within the nodalization of the primary, secondary, and process systems. All this information is compared against the acceptance criteria or requirements of the various engineering systems of the plant to verify compliance or propose improvements to meet them. The SimFase1 simulator is highly versatile in this regard, allowing for parametric studies to optimize maneuver design parameters and/or the systems involved.

The main advantage offered by this tool is the ability to model, at an appropriate level of detail and with relatively low computational cost, the integrated operation of all of the systems of the plant. This allows for the observation of interactions (both expected and unexpected) among these systems throughout operational maneuvers as well as transients caused by operational events.

## CONCLUSIONS

The engineering verification simulator for the CAREM-25 reactor was presented. This simulator was developed in the Process Control Department of CNEA to be used as an interactive graphic simulator to support the engineering of the CAREM-25 Project. This simulator has models programmed in RELAP5 and Matlab/Simulink, which exchange variables during the simulation. Additionally, it has an ad hoc user interface that allows actions to be taken on the models during the simulation.

This simulator constitutes one of the initial phases of the total scope simulator that will be used for operator training, as it has several of the models that the said simulator will have. The models that constitute it were mentioned, and the user interface was described along with the types of transients that are possible to simulate to carry out analyses of interest in different technical areas of the CAREM-25 Project. The main analyses carried out with this tool consist of verifying the design of the main reactor regulations during startup and shutdown maneuvers, as well as in the event of initiating events, evaluating the interaction of different process systems with the reactor and the performance of the regulations. Additionally, it will be possible to evaluate the control logic programmed in the control system through the connection of the engineering simulator with the Siemens control system.

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2. This is not the whole list of postulated events, but only a subset included in a preliminary version of the simulator. [↑](#footnote-ref-3)