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PART-TASK SIMULATOR
FOR A WWER-440 NUCLEAR POWER PLANT SUBSYSTEM

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B.K. Szabó: Part-task simulator for a WWER-440 nuclear power plant subsystem. KFKI-1988-34/G,M

ABSTRACT

PC-based part-task simulators for simulating subsystems of nuclear power plants are cost-effective tools for operator training. This simulation technique has been studied in the Central Research Institute for Physics, and a simulator "frame" has been developed to facilitate fast development of such simulators. The first application simulates the Neutron Flux Monitoring System of WWER-440 nuclear power plants.

Б.К. Сабо: Микро-тренажер для подсистемы АЭС типа ВВЭР-440. KFKI-1988-34/G,M

АННОТАЦИЯ

Тренажеры, симулирующие подсистемы АЭС на профессиональной микро-ЭВМ, являются относительно дешевым средством подготовки операторов. При изучении этой техники симуляции в Центральном институте физических исследований ВАН была изготовлена т.н., "рамка симулятора" для облегчения быстрой разработки таких тренажеров. Первое применение этой "рамки" - разработка микро-тренажера системы АКНП для АЭС типа ВВЭР-440.

Szabó B.K.: Mikroszimulátor VVER-440 tipusu atomerőmű részrendszerének szimulációjára. KFKI-1988-34/G,M

KIVONAT

Az atomerőművi részrendszereket szimuláló un. mikroszimulátorok, amelyek professzionális személyi számitógépen futnak, az erőművi operátorképzés hasznos, a teljes léptékű szimulátorhoz képest igen olcsó eszközei. E szimulációs technika tanulmányozása során a KFKI-ban kifejlesztésre került egy szimulációs keretrendszer, amely lehetővé teszi ilyen szimulátorok gyors, hatékony fejlesztését. E keretrendszer első alkalmazása a VVER-440 tipusu atomerőművek Neutronellenőrző Rendszerét szimulálja.

CONTENTS

1. Introduction

Training simulators play an increasingly important role in the nuclear industry. In addition to full-scope replica simulators, part-task trainers have recently been developed in various countries to simulate subsystems of nuclear power plants [1-5]. These part-task simulators are mostly based on microcomputers and use graphic displays. They simulate only one subsystem (or a few), in order to help operators understand the behaviour of the subsystem and gain operating skills [1].

The possibilities of developing a part-task simulator were studied in the Central Research Institute for Physics, Budapest, and a "frame" for such a simulator was developed. For the first application, the Neutron Flux Monitoring System of the Paks Nuclear Power Plant was selected as the subsystem to be simulated. This paper describes the general simulator "frame" and the application.

2. Advantages of part-task simulators in training

The advantages of simulators in training are well known. This paper deals only with the aspects of using part-task trainers in addition to (or sometimes as an alternative to) full-scope simulators.

Full-scope simulators include a replica of the control room, duplicating the entire man-machine interface of the simulated plant, thus providing opportunity for trainees to acquire all the skills necessary for operating the plant.
However, there are phases of operator training when the trainees study the characteristics and behaviour of individual subsystems of the plant rather than the whole. Part-task trainers can serve this purpose better since, by eliminating extraneous attention demands, they allow the trainee to concentrate on the particular subsystem. They can be useful for teaching operations which are particularly important or difficult to perform. The emphasis is on functional fidelity (behaviour of the subsystem) rather than physical fidelity (exact replica of control panels and other equipment) [5].

There are other advantages of part-task simulators justifying their use in operator training:

- They can be developed in a much shorter time than full-scope simulators. They can be ready well before the commissioning of the plant thereby providing training before the full-scope simulator is completed.
- If a plant is modified, part-task simulators can be updated much more easily than a full-scope simulator. Thus they can function as trainers for the modified plant, before the modifications are actually carried out either on the plant or its full-scope simulator [2].
- They provide plant-specific training for those plants which have no full-scope simulator (e.g. because it is not economically worthwhile to build a full-scope simulator for a particular plant due to the fact that there are existing full-scope simulators for other similar plants).
- Their hardware is inexpensive since they are usually implemented on PC-based workstations. Their most expensive hardware component is the graphic display and a touch-sensitive screen (if the latter is used at all).

3. Hardware considerations

The choice of suitable hardware is of fundamental importance in simulator projects. The two most important criteria are:

- Performance
  This criterion covers computing power and interfacing facilities. Computing power involves not only the speed of the machine, but also the support software.
- Cost

Taking these criteria into account resulted in our selecting an IBM PC compatible computer, in view of its relatively low cost and availability. The computer in question is an 8 MHz AT-compatible computer, equipped with an 80287 arithmetical coprocessor. An EGA display (640 x 350 pixels) was chosen for the graphics display, since this resolution is suitable for displaying schematic diagrams and simplified representations of control panels.

In such a configuration the computer is quite an ordinary PC workstation, which can be used for other purposes besides simulation.

The addition of extra input devices (mouse, dedicated keyboard, touch-sensitive screen) was also considered. The mouse was not found to be really efficient in the kind of input required in a part-task simulator (pushing buttons, turning switches, etc.). A dedicated keyboard would have to be tailored to every particular part-task trainer application, which would involve additional cost and effort. A touch-sensitive screen makes input more realistic, without the aforementioned drawback of the dedicated keyboard. Thus a decision was made to realize input using only the standard PC keyboard, with the possibility of adding a touch-sensitive screen at a later stage of development.

The addition of another display is a further expansion possibility. It could be used for simulation control, alarm messages and plotting of variables [3], while the schematic diagram of the simulated process or a control panel is on the other display.

4. The simulator "frame"

4.1. Introduction

The development of a PC-based part-task simulator for any power plant process involves certain elements (such as numerical solution methods, graphics, etc.) that are always present, regardless of the characteristics of the actual process. Defining a simulator "frame", and defining the interface between the "frame" and the mathematical model of the process to be simulated makes simulator development easier.

Our simulator "frame" consists of a set of subroutines and auxiliary programs.
The subroutines are routines of a numerical integration package, input, graphics and executive routines.
The auxiliary programs facilitate the creation and modification of the simulator. The most important auxiliary program is a picture editor.

4.2. Mathematical tools

A FORTRAN simulation package was adapted to the needs of a PC-based simulator. This package supports the numerical solution of ordinary differential equations that may contain severe nonlinearity [6]. In this implementation of the package, the Fowler-Warten nonlinear second order stiff method is used as the integration method [6].
This numerical integration package, together with a water thermal properties library which calculates the heat properties of the coolant, has proven to be efficient in the simulation of nuclear power plant processes [7-9].

4.3. Graphics tools

An EGA graphics package with FORTRAN callable routines was selected for the simulator. Due to speed problems, it was necessary to add high-speed text-handling routines written in assembly language.

A simple but useful picture editor was developed to facilitate design and modification of pictures. Without this tool it would be necessary to re-compile and re-link the program every time a picture is re-designed. With the picture editor, picture design and modification are interactive. The picture editor handles picture elements called icons. There is an interface defined between the "iconic level" of the picture editor and its other, higher levels. The "iconic level" handles the actual drawing and updating of icons. All graphics-package dependences are handled on this level. Thus the picture editor can easily be implemented on other graphics packages, if necessary.

The picture editor stores the pictures in disk files, and the application program can read these disk files into common data areas. The dynamic update of icons is done by the application program through the pre-defined interface to icons.

The actual icons that make up the picture are of pre-defined icon types, such as line, circle, text, pushbutton, indicator, etc. The complexity of icons is not restricted and anything can be realized that is within the capabilities of the graphics package. This is also true for the dynamic update of icons (colour, size, shape, etc.).

The construction of a new icon type consists of describing the new icon type for the picture editor and writing the subroutines which draw the static and dynamic parts of the icon. The new icon type is placed into the icon library by an icon library manager program.

The features of the picture editor include

- loading/saving a picture data file
- adding icons to the picture data base
- deleting icons
- modifying icon parameters
- dynamic icon update

4.4. Input, executive services

At present the simulator receives input only from the keyboard. Keyboard handling routines have been developed for this purpose. Special attention has to be paid to the "reflection" of input actions (e.g. that of pushing a button) on the display. Due to the performance of the hardware used, the simulation cycle time is longer than what is acceptable for the delay of, for example, a switch or pushbutton update. Thus input actions are noticed and "reflected" several times in a simulation cycle.
Other executive services include control of simulation, real-time synchronization and display update control. Trending services (collecting and plotting samples of selected variables) are not included in the present version, but will be available in the future.

The organization of simulation control reflects the structure of the numerical integration package. During initialization, the initial condition is loaded from a file, auxiliary variables and tables are set, the picture data file is read and the picture is initialized. The calculation of the new state of the simulated process is coupled with input servicing. At the end of the simulation cycle, display update and other executive tasks are carried out.

4.5. Simulator development using the "frame"

The tasks of developing a simulator for a plant subsystem, utilizing the simulator "frame" described above are the following:

After making a decision on the scope of simulation, and on the input and output of the simulator, the mathematical model of the process has to be developed, in the form required by the numerical integration package.

The pictures to be displayed by the simulator have to be constructed with the aid of the picture editor.
Dedicated input interpretation and picture update routines are to be written.

5. The Neutron Flux Monitoring System simulator

5.1. Introduction

Outside some small models for testing purposes, the Neutron Flux Monitoring System (NFMS) simulator is the first part-task simulator application which has been built using the simulator "frame" described above.
Our aim was to create a simulator with which the behaviour and operation of this particular nuclear power plant subsystem can be demonstrated.

5.2. Functions of the Neutron Flux Monitoring System

The Neutron Flux Monitoring System monitors the flux of thermal neutrons in the reactor of a WWER-440 type nuclear power plant unit, in all possible operational states of the reactor.

There are three types of neutron detectors for optimal measurement of the neutron flux in a wide range. Thus there are three measurement ranges: source, intermediate and power range.

The NFMS consists of three separate systems:
- main system
- system for the monitoring of refuelling
- system of the emergency control room

Each of the first two systems consists of two identical but independent subsystems which operate in parallel.

Both subsystems of the main system have three independent measurement channels for all three measurement ranges.
The other two systems of the NFMS are equipped only with source-range detectors.

The NFMS provides the following information, displayed in the control room:

- on CRT and digital display
    - neutron power and reactor period in the form of bar diagrams, for all channels of the main system; the limits of the measurement ranges and the safety limits also appear on the bar diagrams
    - neutron power and reactor period from the selected channel (or the average of all channels), in digital form
- status lights
    - indicating the current measurement range (source, intermediate or power range)
    - indicating beginning and end of the measurement ranges ("2 out of 3" logic)
    - indicating whether the signal processing units of the channels are operating or out of order
    - to warn that the safety limit of the power measurement should be modified (if the measured value is too close to - or too far from - the limit that has been set) ("1 out of 3" logic)
    - safety signals derived from how close the values of power and period have approached their limits ("1 out of 3" logic)
- on control panels
    - on analog recorders: indication and recording of neutron power and reactor period from the selected channel (or the average of all channels)
    - position of the movable (source and intermediate range) detector units
- sound signals (indicating power level in source-range channels at low power levels)

Most of the above information is not only displayed but also passed on to other systems of the plant.

The operator can control the NFMS by

- selecting the measurement range (source, intermediate or power range). There is also a possibility for automatic range selection. Selection of a range is done by pushing down the corresponding button. Automatic range selection is set when none of the buttons is in a "pushed-down" state. Incorrect manual range selection may result in automatic safety operations in the reactor.
- setting safety power level limits for the three measurement ranges. The setting can be done in discrete steps, with thumb-wheel switches.
  Incorrect setting may cause automatic safety operations.
- selecting the measurement channels to be displayed on the digital display, by pushing the corresponding button.
- manual control of the movable detectors (the detectors can also be controlled automatically by the NFMS, when change of measurement range makes it necessary). Manual detector control and the selection between manual and automatic modes is controlled by handswitches.

5.3. Scope of simulation

As mentioned above, the NFMS consists of three separate systems, which are totally independent of each other.
They all have their own detectors, signal processing units and control boards. Only the main system is used routinely, the other two are auxiliary systems. The principles of operation are the same for all three systems.
In our NFMS simulator only the main system is simulated.

The two subsytems of the main system are identical. They perform the same operation and operate in parallel.
Except for the simulation of malfunctions, there is nothing to justify the representation of both of these subsystems in the simulator. Thus only one subsystem was included in the scope of simulation.

The measurement channels are simulated but the detectors themselves (as separate units) are not. Thus the positions of the detectors are not displayed, and the control of detectors is assumed to be automatic.

The sound signals (indicating power level) are not simulated.

The analog recorders are not simulated. Their function will be taken over by the - planned - trending services of the simulator "frame".

All other input and output functions of the NFMS described in Section 5.2. are simulated.

In order to demonstrate the behaviour of the NFMS, it was necessary to simulate power plant functions outside NFMS:

- Control rod operation:

  Since the aim was not a detailed simulation of rod control, only manual control of a rod group is simulated. Automatic rod control - except for safety operations - is not simulated.
  On the simulated control panel, handswitches necessary for rod control operations are displayed. The positions of manually controlled rods are also displayed.

- Safety operations:

  The alarm signals generated by the NFMS initiate safety operations. Four types of safety operations are possible:
  LEVEL 1: Scram. All control rods fall into the core (speed: 250 mm/sec). This is an irreversible operation.
  LEVEL 2: Fast shutdown. The control rod groups fall into the core, one after the other (there are 6 groups altogether). This operation stops if the conditions initiating it cease to exist.
  LEVEL 3: Power reduction. The control rod groups move into the core, one after the other, at a speed of 20 mm/sec. This operation stops if the conditions initiating it cease to exist.
  LEVEL 4: Inhibition of power increase. Control rod movement out of the core is inhibited.

  All four safety operations can also be initiated by pushing the corresponding button. These buttons are also simulated.

  The conditions initiating these safety operations are summarized in Section 5.4. .

5.4. The model

The components and structure of the model can be seen in Fig. 1.

The neutron kinetics, fuel kinetics and average channel models were existing models developed earlier, and they are described in [7] in detail. They have the following features:

The neutron kinetic model is a one-point model. Prompt jump approximation is used. Iodine - xenon poisoning is not simulated. Delayed neutrons are represented as one group. The equations of the neutron kinetic model are the following:

N = 1 * lambda * C / (beta * (1 - ro))

where

N - neutron power
1 - lifetime of prompt neutrons
lambda - decay constant for the delayed neutrons
C - concentration of the delayed neutrons
beta - the ratio of delayed neutrons to the total number of neutrons
ro - reactivity

dC/dt = (beta / 1) * N - lambda * C

where dC/dt is the time derivative of the delayed neutron concentration

The reactivity equation, which takes temperature feedback into account, is the following:

ro = ro(ext) + gd * (Tf - Tfn) +
+ gden * (rw -rwn) + gmod * (Tw - Twn)

where

ro(ext) - change in external reactivity, originating from rod movement
gd - temperature coefficient of the fuel element
Tf - fuel temperature
Tfn - nominal steady-state value of Tf
gden - density coefficient of the moderator
rw - density of the moderator
rwn - nominal steady-state value of rw

gmod - temperature coefficient of the moderator
Tw - temperature of the moderator
Twn - nominal steady-state value of Tw

The core is modelled as a set of average channels, each of them representing a fuel assembly with a section of the coolant. All channels are taken to be equal. A channel is divided into the following sections:

- fuel pellet
- gas gap and cladding
- coolant

The fuel kinetics model has to solve a one-dimensional heat conduction problem in a body whose heat is generated in the whole volume and the heat conductivity coefficient is a nonlinear function of temperature. Axial heat conductivity is neglected. Average fuel temperature can be calculated from the heat balance equation:

$$Vf * rf * cf * dTf/dt = QV - Qsf$$

where

Vf - volume of fuel assembly
rf - density of fuel
cf - specific heat of fuel assembly
QV - heat generated in fuel assembly
Qsf - heat transferred from the fuel to the coolant
dTf/dt - time derivative of the average fuel temperature

The heat generated in one fuel assembly is

$$QV = N * (1 - delta) / nf$$

where

N - neutron power
delta - ratio of heat generated in moderator
nf - number of fuel assemblies

The heat leaving the fuel is

$$Qsf = lambdf * Lact * Rf * 4 * \pi * (Tf - Tsf)$$

where

lambdf - average heat conductivity coefficient of fuel
Lact - active length of fuel assembly

Rf - radius of fuel pellet
Tf - average fuel temperature
Tsf - surface temperature of fuel

The average heat conductivity coefficient as a function of temperature is

```
lambdf = eps1 / ( 1 + eps2 * Tsf )
```

where eps1 and eps2 are constants.

The heat transfer in the cladding is neglected.

Since a channel of average power is modelled only for normal working and alarm conditions, boiling practically never occurs. Thus the model simulates one-phase flow and convective heat transfer. The heat transfer to the coolant is

```
Qsf = alpha * Fca * ( Tsf - Tw )
```

where

alpha - convective heat transfer coefficient
Fca - surface of cladding
Tsf - average surface temperature
Tw - average temperature of coolant

The heat transfer coefficient can be determined as

```
alpha = ( lambdw / Dw ) * ( 0.023 * ( Re**0.8 ) *
        * ( Pr**0.4 ))
```

where

lambdw - heat conductivity coefficient of the coolant, as a function of average pressure and power
Dw - equivalent hydraulic diameter of average channel
Re - Reynolds number of coolant as a function of pressure and power
Pr - Prandtl number of coolant as a function of pressure and power

The energy balance equation for the coolant is

```
Mw * dhw/dt = QM + Qsf - QG
```

where

Mw - equivalent mass of water in the channel

dhw/dt is the time derivative of the average water enthalpy
QM - heat generated in the coolant of the channel
QG - heat taken away by the coolant flow

The average enthalpy can be expressed as the average of coolant enthalpies at the point of entering and leaving the core:

hw = 0.5 * (hwin + hwout)

The mass of water is

Mw = Vw * rw + (Mm * cm / cw)

where

Vw - volume of coolant in average channel
rw - density of coolant
Mm - mass of the construction material in an average channel
cm - specific heat of construction material
cw - specific heat of water (function of pressure & temperature)

The heat generated in the coolant can be written as

QM = N * delta / nf

The heat taken away by the coolant flow is

QG = Gaz * (hwout - hwin)

where

Gaz is the mass flow of the coolant in the average channel

The NFMS logic model receives the neutron power provided by the neutron kinetics model, and calculates the reactor period from it.
The model also receives input from the operator: measurement range selection, safety power limits for the three ranges and channel selection for the display.
If measurement range selection is in automatic mode, the model determines the appropriate measurement range.
From these data, it provides safety signals for the safety

system logic, and prepares logic and numerical data for the graphic picture update.

The NFMS logic model provides the following signals for the safety system logic:

- NFMS safety signals of level 1:
    - Power has reached its safety limit in any power-range measurement channel
    - Power range has been selected, but the measured power value is lower than the lower limit for power-range measurement, for any power-range channel
    - Power has reached 110% of the nominal power value (1375 MW) in any power-range channel
    - Reactor period is equal to or less than 10 sec in any channel of the current measurement range
- NFMS safety signals of level 3:
    - Power has reached its safety limit in any source-range measurement channel
    - Measurement is in the source range, but the measured power value is lower than the lower limit for source-range measurement, for any source-range channel
    - Power has reached its safety limit in any intermediate-range measurement channel
    - Measurement is in the intermediate range, but the measured power value is lower than the lower limit for intermediate-range measurement, for any intermediate-range channel
    - Power has reached 95% of its safety limit in any power-range channel
    - Reactor period is equal to or less than 20 sec in any channel of the current measurement range

The safety system logic model controls the safety operations of safety levels 1...4, by evaluating manual actions of the operator and the safety signals received from the NFMS logic model.
The following conditions can initiate safety operations:

- Level 1:
    - NFMS Level 1 safety signal
    - Pushing the "Level 1" button (operator action)

- Level 2:
    - An NFMS Level 3 safety signal has been valid for at least 10 sec
    - Pushing the "Level 2" button

- Level 3:
    - NFMS Level 3 safety signal
    - Pushing the "Level 3" button

- Level 4:
    - Pushing the "Level 4" button

In a real power plant the safety system logic receives safety signals from other subsystems as well, but here only the NFMS is modelled.

The control rod model is a simple model of the 37 control rods, which are in 6 groups. In this model all rods are taken to be equal, and their reactivity value is approximated as a linear function of their position. Manual rod control moves the rods at a speed of 20 mm/sec. The rod control actions initiated by the safety system are described in Section 5.3.

5.5. Realization

The display picture can be seen in Fig.2. It is a functionally equivalent representation of one board in the control room. The rod position display - which can be seen in the upper right corner - is actually on another board in the control room.

Fig.2 shows the system in steady state, with the power at nearly 100% of the nominal power value.

The framed section in the middle represents a CRT displaying bar diagrams of power and period values, for all channels of all measurement ranges. (Due to steady state, the reciprocal of the reactor period is too small to be displayed in Fig.2.)

On the left of the CRT, there are two digital displays, showing the power in % and the period in seconds.
In the upper part of the picture the text elements are 22 status lights, which can be turned "on" and "off": displayed in two colours of different intensity. (Unfortunately, colours and intensity are not shown in the black-and-white picture.)
The thumb-wheel switches for setting the power safety limits are below the CRT. On the left of these, the framed letters F, K, E represent the buttons of the measurement range selection unit.
The channel selection unit is below them.
The row of handswitches occupying the lower part of the picture are for rod control.
The column of circular objects on the left are buttons for initiation of safety actions of level 1...4.
The picture consists of about 100 icons.

The simulator can start from initial states prepared in advance. The simulation cycle is 1 sec. Some transients may exceed this temporarily, but the simulator executive can later make up for the lost time. The delay is caused not only by calculations, but also by intensive picture update during transients.

In the present version of the simulator, the three channels belonging to each of the three measurement ranges are all alike, they all "measure" the same value. A further development possibility is the introduction of channel malfunctions.

6. Conclusion

The "frame" developed for part-task simulators has proven its efficiency in the first application. With this "frame" it is possible to develop other cost-effective part-task simulators within a comparatively short time.
The application, the Neutron Flux Monitoring System simulator, is a tool that helps the trainee understand the operation of this subsystem and gain operating skills.

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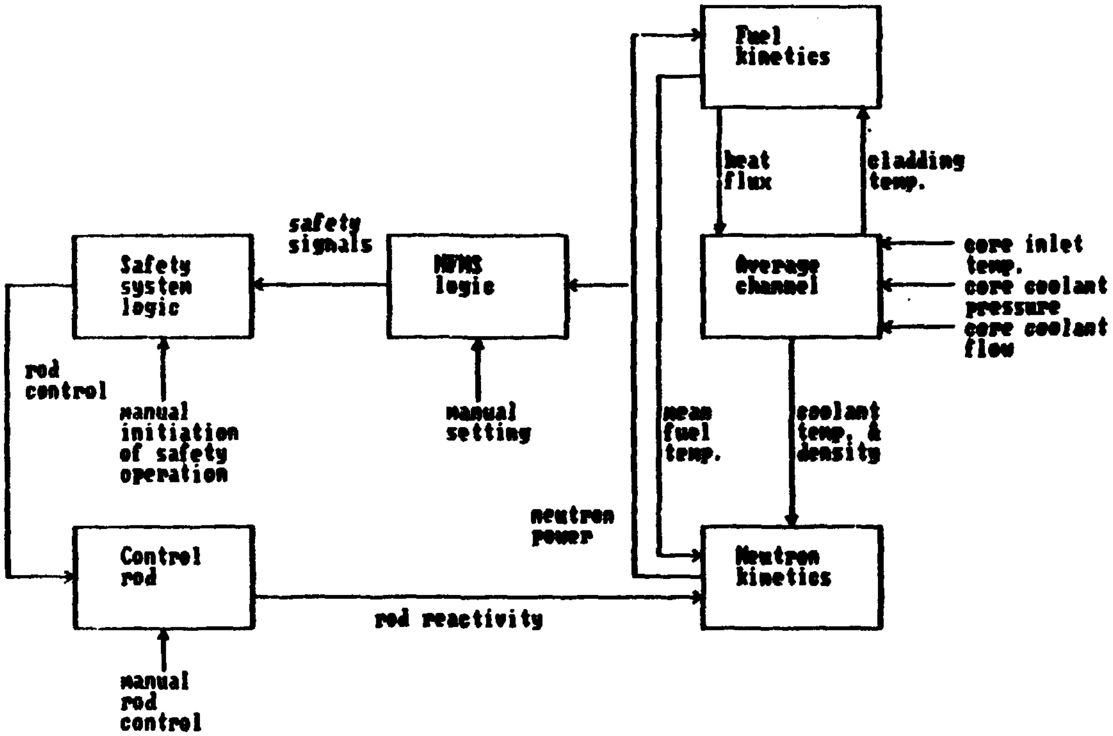

Fig.1. Model structure

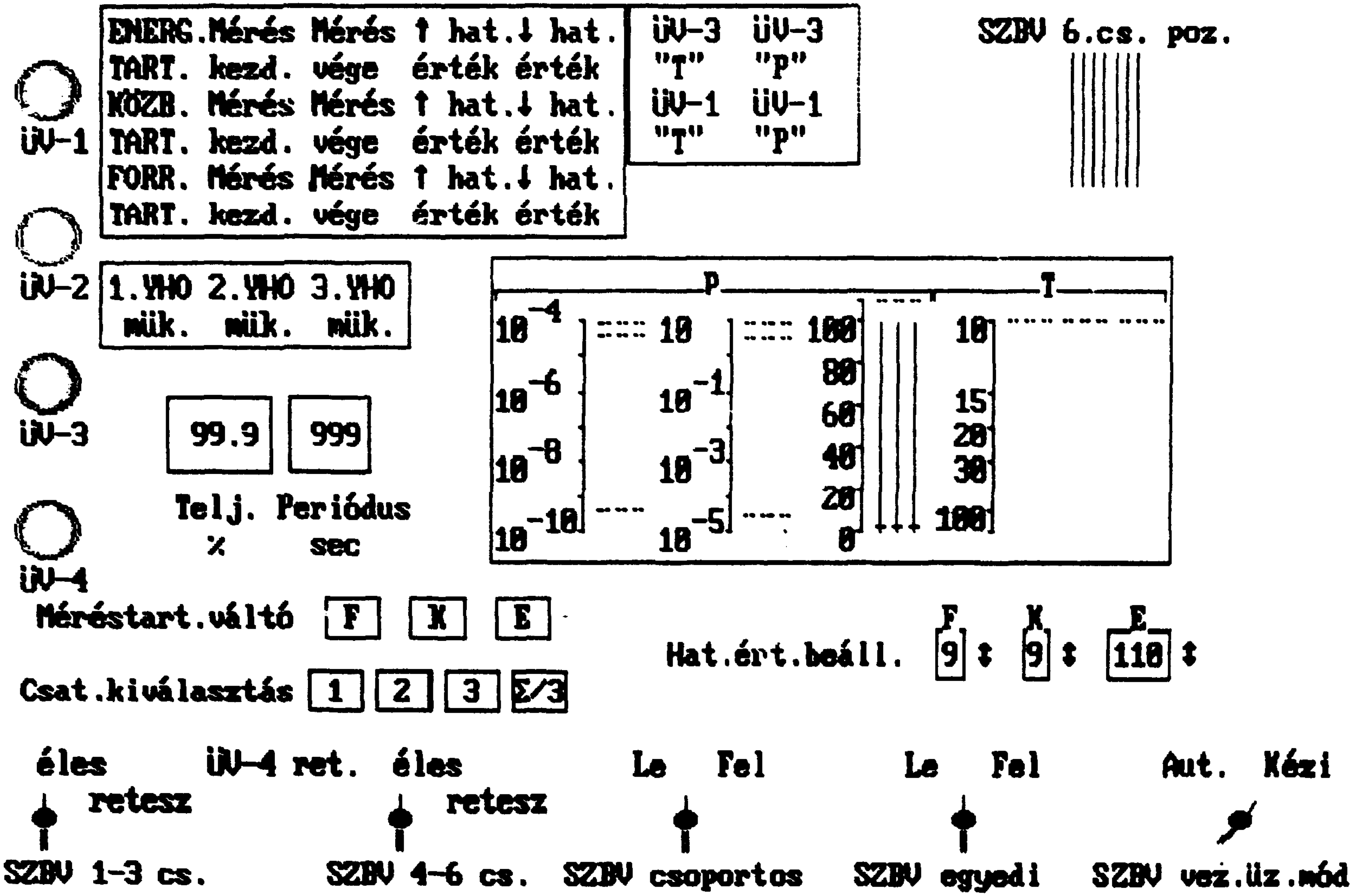

Fig.2. Simulator display

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