ON THE USE OF DYNAMIC MODELLING FOR THE DESIGN OF IRF

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ABSTRACT

The multi-purpose high-flux Irradiation Research Facility (IRF) reactor has been proposed by AECL as a replacement for the venerable NRU reactor at Chalk River, and the pre-project design of IRF is currently underway. As part of this design effort, we are currently modelling the dynamic response of the reactor and especially that of the Reactor Regulating System (RRS). The tool chosen for this work is the MATRIXx family of programs, including XMath, SystemBuild and DocumentIt.

The SystemBuild tool allows users to specify a complete model by graphically interconnecting a set of modules (SuperBlocks) and/or "primitives". Each module, in turn, can be defined graphically by interconnecting a further set of sub-modules and/or "primitives". The system supports both continuous (analog) as well as discrete (digital) modules at the same time. Thus, it is possible to accurately model a continuous process coupled to its computer-based control system. The frequency response of the system can be extracted from the same model.

The model will be used for control system stability analysis and to choose appropriate design parameters for various controllers and dynamic compensators within both the RRS and other important controllers in the system. The whole system can then be tested using various manoeuvres such as start-ups, shutdowns and step perturbations. It can also be used to verify that the design functions well under extreme conditions such as those which might occur at the beginning or end of the fuel cycle, or when attempting to override a poison-out. The model can also be of practical assistance to other designers in choosing the various parameters involved (e.g., step size of the stepping motor drives for the control absorber rods (CARs), or rundown time of the main primary coolant system pumps).

The model currently consists of:

- point- or 7-node neutron kinetics with temperature and xenon feedback,
- 1 or 2 sets of log, linear and log rate amplifiers,
- the RRS (flux) control algorithm,
- 1 or 2 banks of CAR drives,
- the primary coolant circuit with 2 pumps and two main heat exchangers, and
- secondary temperature control valve(s) and controller(s).

This model-based design process has proven very useful for the MAPLE reactor design, and it is expected to be equally important in designing the even more complex IRF system.

INTRODUCTION

The multi-purpose high-flux Irradiation Research Facility (IRF) reactor [1] has been proposed by AECL as a replacement for the venerable NRU reactor at Chalk River. The IRF is a 40 MW split-core MAPLE-type reactor. The main part of the reactor has 32 fueled sites. Each contains either a hexagonal fuel bundle of 36 elements or an 18-element cylindrical fuel bundle. The elements are aluminum fuel rods containing 20% enriched U_3Si_2Al metal matrix composite. The eight (four on each side) 18-element fuel bundles are associated with movable hafnium Control Absorber Rods (CARs), which surround the fuel. The main reactor is cooled by low-pressure, low-temperature light water, which flows upwards through the core. Surrounding the core is a large tank of heavy water, called the reflector. In the centre, between the two halves of the split core are three Horizontal Test Sections (HTSs), each capable of containing up to three CANDU® bundles under CANDU-like coolant conditions. These HTSs are also surrounded by reflector heavy water. In addition, there are fast neutron sites, vertical fuel-test facilities, material irradiation sites and neutron beam research facilities.

The pre-project design has been underway for nearly two years. As part of this design effort, we are modelling the dynamic response of the reactor to various desired changes and upsets. In particular, a major effort is directed towards modelling the response of the Reactor Regulating System (RRS), which controls the reactor flux/power via the CARs, to setpoint changes, for example, during shutdowns and startups. These models are used to design control strategies, and select gains and dynamic compensators, to give an optimal or nearly optimal response under a variety of conditions. A similar dynamic modelling exercise was conducted as part of the MAPLE-X10 design and proved very useful.

MODELLING TOOLS

It is preferable to perform simulation and modelling on a commercially-supported platform which includes much of the desired functionality. In the past, we have simulated reactor control systems using the following platforms:

- analog and analog/hybrid computers (1960s and 1970s),
- the FORSIM package [2] (1980s and 1990s), and
- the EASY5W package (also in 1990s).

The new tool chosen for this work is the modern MATRIXx family of programs, including XMath, SystemBuild and DocumentIt, purchased from Integrated Systems Inc. (ISI). MATRIXx runs on a Pentium-based personal computer under Windows NT; a workstation (UNIX) version is also available.

XMath, the basis of the package, is a general purpose matrix algebra tool. In the simulation context, it allows the user to calculate and specify model and simulation parameters. It also facilitates plotting. Scripts can be set up which perform repetitive functions, such as calculating initial conditions, automatically. In fact, the user does not have to specify the initial conditions of each state, the system itself can find them from the steady-state solution for the model.

The SystemBuild modelling tool allows users to specify a complete dynamic model by graphically interconnecting a set of modules (SuperBlocks) and "primitives". Each module, in turn, can be defined graphically by interconnecting a further set of sub-modules and primitives. The primitives, which are supplied by ISI, include:

- algebraic blocks (gain, sum/difference, multiply, divide, polynomial, etc.);
- piece-wise linear blocks (dead-band, saturation/limiter, absolute value, quantization, pre-load);
- dynamic blocks (n^{th} order integrator, state space, transfer function in z, hysteresis, time delay, PID controller, second-order system);
- trigonometric blocks (sin, cos, tan, and their inverses, etc.);
- power-exponential-logarithmic blocks (square-root, log, exponential, power);
- coordinate transformation blocks (Cartesian to polar, 3-axis rotation, etc.);
- signal sources (step, ramp, sinusoid, general, random numbers, etc.);
- logical blocks (shift register, AND, OR, NOT, relational comparison, switch, binary-to-decimal, etc.);
- user-written blocks;
- knowledge-based blocks (expert system, fuzzy logic);
- interpolation blocks (linear, cubic spline, etc.); and
- SuperBlocks (collections of other blocks).

Note that MATRIXx supports both continuous (analog) as well as discrete (digital) modules in an interconnected system. Thus it is possible to accurately model a continuous process coupled to its computer-based control system.

The frequency response of the system can be extracted from the same model which gives the time response, thus giving the user two different views of the system. Previous modelling codes (e.g., CATHENA) could do either one or the other but not both.

The DocumentIt tool provides a semi-automatic method for documenting the model and its various modules and sub-modules. This documentation comes from the model itself.

Additional tools are available in the MATRIXx package and provide robust control system design, simulation animation, and ADA controller-code generation. The package is periodically updated and enhanced by ISI.

The use of this modern dynamic simulation and analysis tool, in principle, should increase productivity and reduce turnaround time, when simulating new scenarios, or testing modifications to either the plant, its instrumentation or its controllers.

MODEL

The IRF model being developed is presently designed to work in all normal operating conditions, and to cover single faults that are likely to occur over the life of the reactor. The range of validity is up to the first trip point. In a practical sense, for the IRF, this implies that the primary coolant remains a single-phase fluid. This single-phase assumption greatly simplifies the heat-transport, fluid-flow modelling. The model is not meant to be a fully qualified safety-analysis code, which would be capable of analyzing severe accidents; CATHENA is the chosen tool for safety analysis. However, it is meant to give designers and operators a very good idea of how the reactor will function under all expected conditions.

Presently, we are planning to incorporate the following modules in our module library:

- point neutron kinetics (6 delayed groups plus 9 photoneutron groups),
- 7-node neutron kinetics (1-D diffusion),
- xenon,
- logarithmic amplifier,
- log rate and linear rate amplifiers,
- the RRS (flux/power) control algorithm,
- CAR drives and conversion to reactivity,
- pump,
- heat exchanger,
- the primary coolant circuit with two pumps and two main heat exchangers, and
- primary temperature control valves and controllers.

The point-kinetics, log amplifier, log rate amplifier, RRS controller and CAR drive provide the basic RRS flux control loop at low power, while at high power, the linear and linear rate amplifiers are also used. Internal reactivity feedback is provided by power, reactor inlet temperature and xenon feedbacks. The reactor inlet temperature is provided by the primary coolant circuit module with its pumps and heat exchangers. The control valves on the secondary side provide primary temperature control. The main RRS loop, with the important feedback sources, is illustrated in Figure 1. The main RRS loop is shown in the SystemBuild format in Figure 2; this loop includes the following SuperBlocks:

nk	reactor kinetics
Tfeedback	temperature/power feedback
Lo, ra_log, ra_lin	flux amplifiers: log, log rate, and linear rate
RRC, RRS_calc_delay	the RRS algorithm, including calculational delay
rod1_cont	single equivalent CAR drive

The RRS algorithm SuperBlock is shown in Figure 3; it uses many of the ISI-supplied primitives.

By connecting the model shown in Figure 2 to a signal source primitive, a simulation can easily be run. Figure 4 is an example showing a power manoeuvre of the MAPLE-X10 reactor from 100% FP to 50% FP over the first 75 s, and then back again.

Because of the split-core IRF design, there is the potential of side-to-side flux tilts driven by xenon. The 7-node neutron kinetics module models one-energy group diffusion in one-spatial direction. It has been shown to be accurate to within 5-10% in comparison to a 2-energy group 26-node model, working on the same reactor kinetics problem. It will be used in conjunction with the xenon module to demonstrate that the flux tilt control algorithm successfully controls the flux shape across the reactor.

The dynamic model of the IRF will be used for control system stability analysis and to choose appropriate design parameters for various controllers and dynamic compensators within both the RRS and other important controllers (e.g., primary coolant temperature) in the system. Control stability is usually specified as a combination of:

- gain margin - should be greater than 5 dB,
- phase margin - should be greater than 40 degrees, and
- over/undershoot - less than 1% at full power.

These limits have been used previously for NRU, NRX [3], and MAPLE-X10 [4] controller evaluations. They should be applicable under all anticipated operating conditions, including steady state at any power level, and during ramp-up from low power to high power.

The whole simulation system (controllers plus reactor) can then be tested using various manoeuvres such as start-ups, shutdowns and step perturbations. It can also be used to verify that the design functions well under extreme conditions such as those which might occur at the beginning or end of the fuel cycle, when attempting to override an xenon poison-out, or when starting up with a colder-than-normal pool. The model is also of practical assistance to other system designers in choosing the various parameters involved, and to operations in developing operating rules for unusual situations. Some of the important parameters that must be chosen are:

- time constants of the linear, log, linear rate and log rate amplifiers;
- time constants for temperature sensors;
- speed and step size of the CAR drive stepping motors;
- dynamic compensators within the RRS control algorithm; and
- PID gains for the PCS temperature controller, and possibly any feedforward terms.

For the IRF, we expect the the model will gradually grow both in scope and detail. For example, ultimately the model will include the HTSs with their loops, and thus it will account for both the effect of the reactor on the HTSs (temperature, pressure and void changes due to changes in reactor power) and of the HTS loops on the reactor (temperature/void reactivity feedback). The middle node of the 7-node kinetics module is used to represent the HTSs. With this expanded model, we can ensure during design that the main reactor flux-control loop, the PCS temperature control loop and the control loops for the HTSs, are satisfactorily co-ordinated. The reactor should be able to startup at full speed (5% PP/s or 3% FP/s) without exceeding limits on any system.

By gradually expanding and improving our library of nuclear modules, the first group of which are listed above, we should be able to configure simulations of any nuclear-related system within a fairly short time-frame. The modules developed to date have followed a rigorous quality assurance procedure, which is suitable for a CSA N286.2 [5] design program. The documentation for each module covers the equation set used, implementation details, any limitations on their use, and a test (verification and validation) report. This extra effort should be repaid in the future as modules are re-used in other simulations.

Flexible tools like MATRIXx support efficient rapid prototyping. However, the use of scripts is necessary to guarantee reproducible simulations, using identical input data and models; this use of scripts requires substantially greater development and documentation effort.

CONCLUSIONS

This model-based design process has proven very useful for the MAPLE reactor design, and it is expected to be equally important in designing the even more complex IRF system.

The development of a library of modules, complete with descriptions, test cases and validation, should lead to a modelling environment which is flexible and easy-to-use, while at the same time providing verifiable results. By re-using modules over several different models and projects the effort involved in software development and documentation pays off.

The model of the IRF reactor being developed has sufficient details in the RRS flux control loop to answer all design questions regarding its operation. In particular, we can evaluate the effects on flux control of amplifier time constants, CAR step sizes, and controller cycle times. Ultimately, it will be expanded to enable evaluation of the integrated reactor control including PCS temperature control and HTS pressure and temperature control.

REFERENCES

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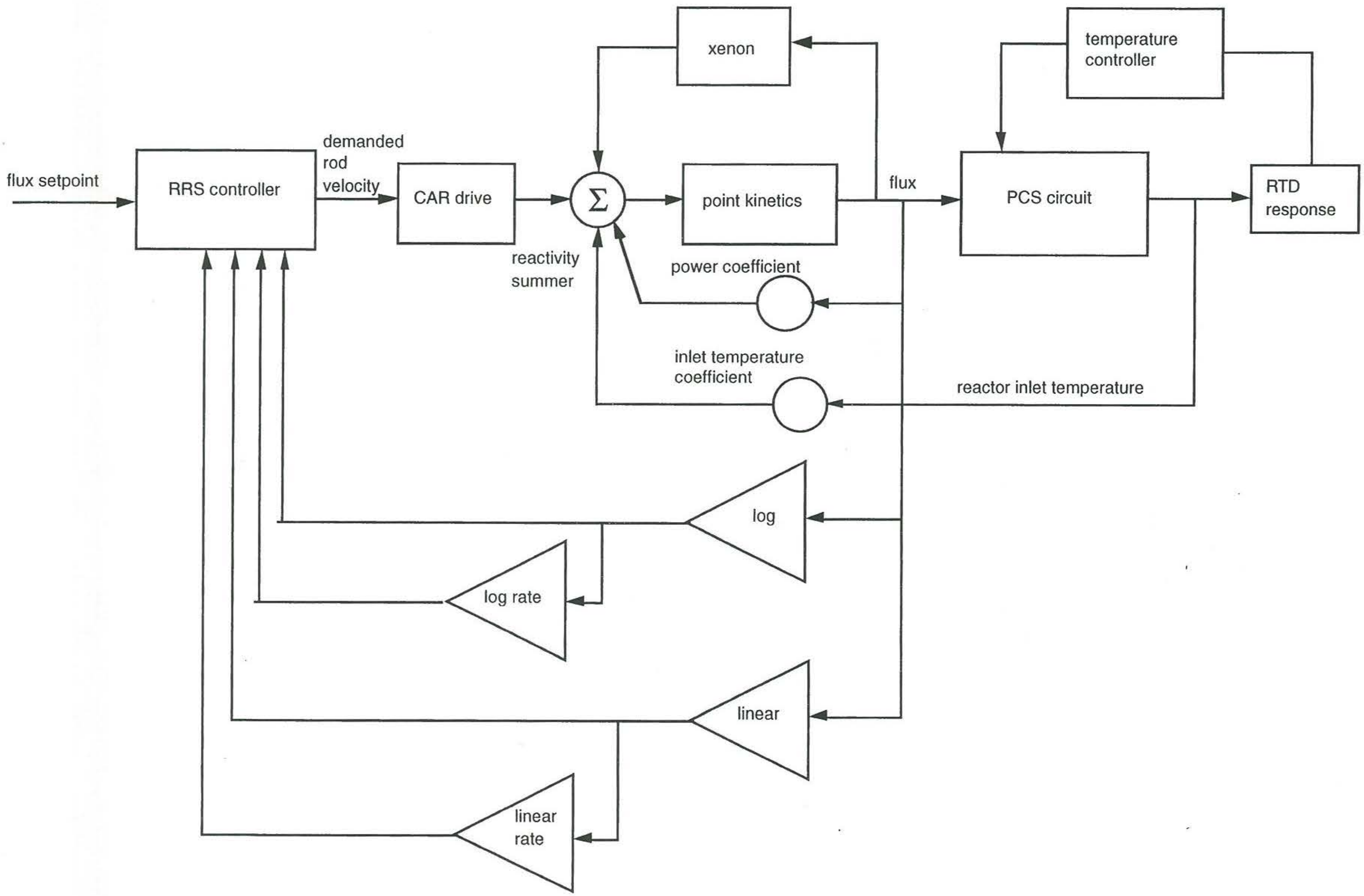

Figure 1: Block diagram schematic showing interconnection of modules

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Continuous SuperBlock	Inputs	Outputs
m2_reactor	2	6

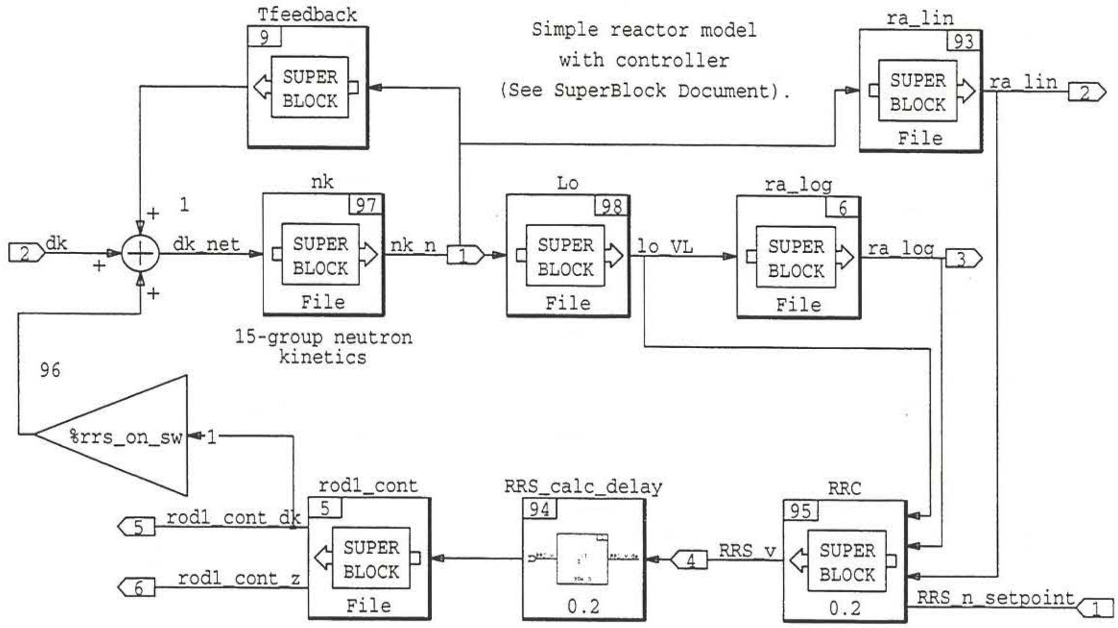

Figure 2: Main RRS control loop shown in SystemBuild format

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Discrete SuperBlock	Sample Period	Sample Skew	Inputs	Outputs	Enable Signal
RRC	0.2	0.	4	1	Parent

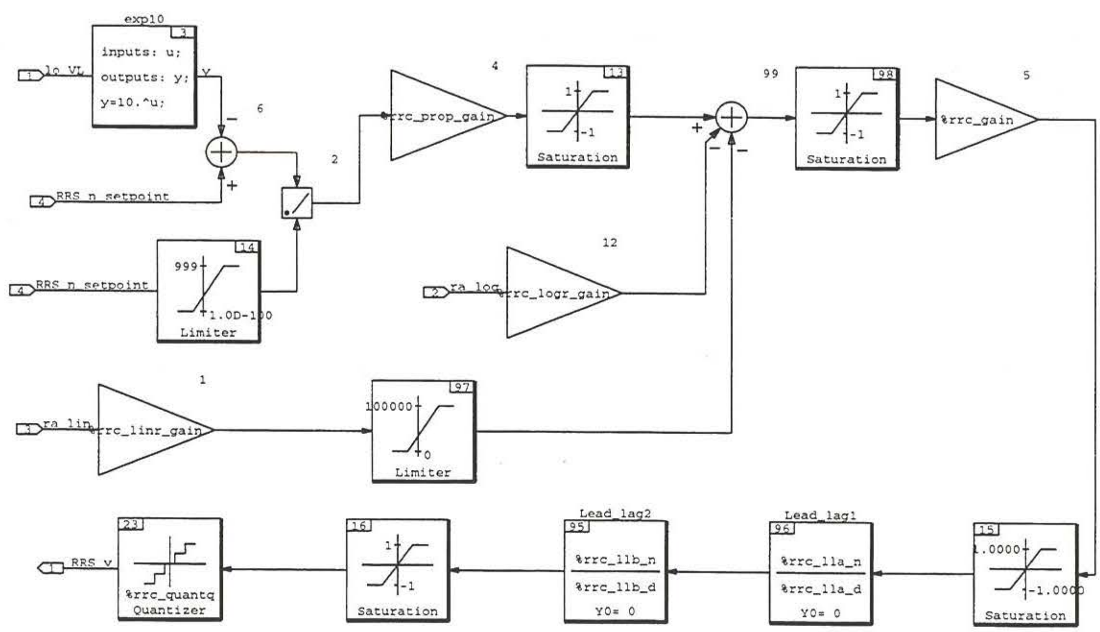

Figure 3: The RRS algorithm SuperBlock RRC, made up of SystemBuild primitives

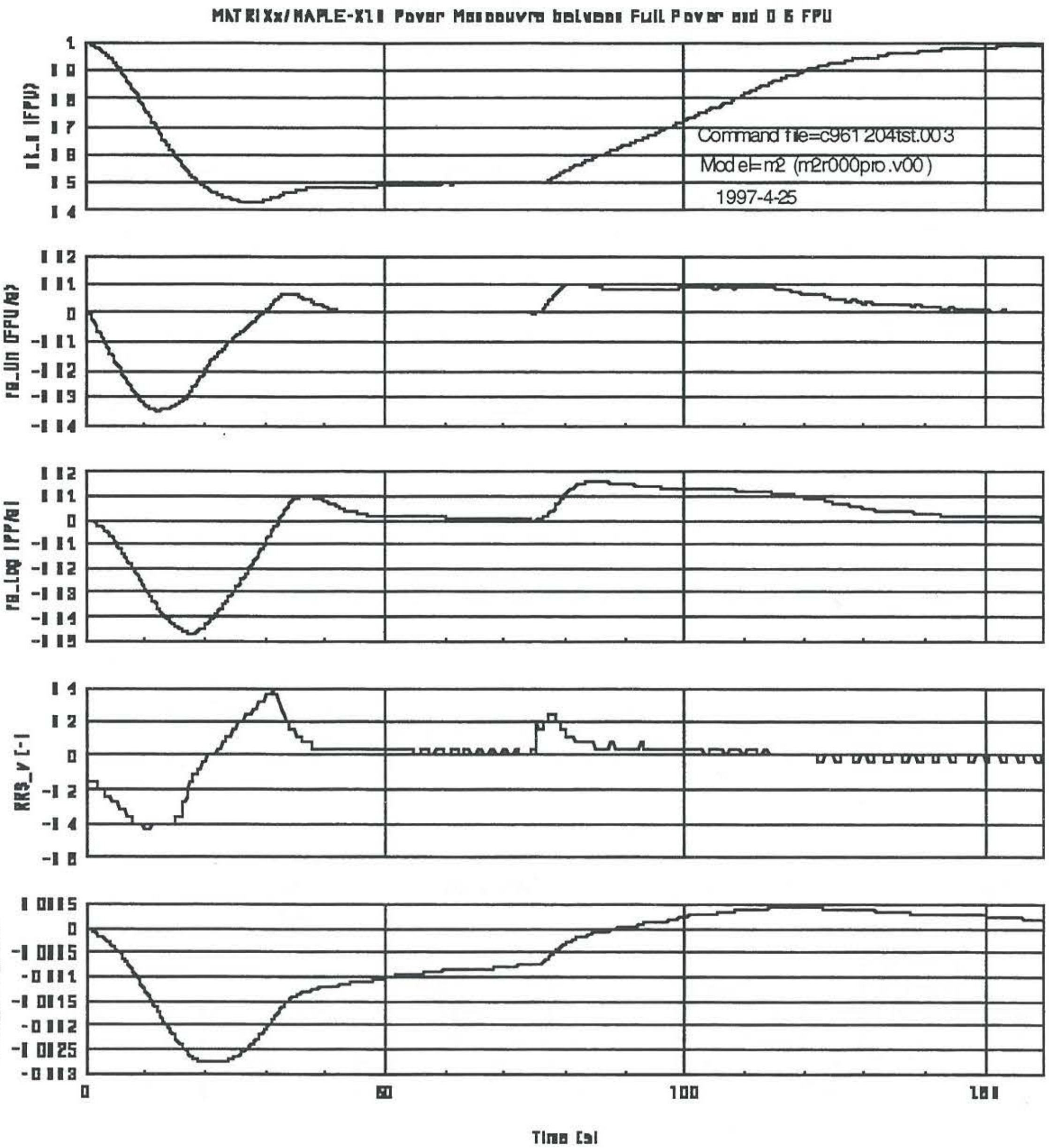

Figure 4: Simulation run showing effect of changing RRS setpoint from 100% FP to 50% FP at time 0 s and back to 100% FP at time 75 s. Traces (from top to bottom) are: normalized neutron flux, linear rate, log rate, CAR velocity, and CAR reactivity.