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International Agreement Report

Coupled RELAP/PARCS Full Plant Model – Assessment of a Cooling Transient in Trillo Nuclear Power Plant

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ABSTRACT

This report presents the methodology to change from a 0-D kinetics core in a RELAP5/Mod3.3 full plant model of Trillo NPP to a coupled RELAP5/PARCS 3-D core. The coupled plant model is assessed against a real cooling transient that deformed the core power axial profile.

The coupled steady state core model was adjusted to a CASMO/SIMULATE calculation by condensing the cross-sections with the SIMTAB methodology. The need of information exchange between RELAP and PARCS during the transient was the reason for two modifications of the coupling between both codes.

- The CASMO/SIMULATE calculation of the initial core conditions correspondent to the date of the transient was performed by Iberdrola Ingeniería.
- The SIMTAB methodology used to build the PARCS input file, the automated tools for core input files mapping and the RELAP/PARCS modifications of control rod and boron content were performed by the Nuclear Engineering Group belonging to the Institute for Industrial, Radiophysical and Environmental Safety (ISIRYM) at the Universitat Politècnica de València (UPV).
- The modifications to the RELAP5 full plant model to couple the 3-D PARCS core, the steady-state adjustments of PDDs, and the transient calculation and analysis were performed by the Thermo-Hydraulic group of Almaraz-Trillo NPPs.

The results of the transient show an almost perfect agreement with plant data for all the compared variables. The comparison of in-core parameters evolution with plant data is also very good and the 3-D simulation allows to perform a more detailed analysis of core behaviour.

This report was prepared by the Thermo-Hydraulic group of Almaraz-Trillo NPPs (CNAT), with the help of the Polytechnic University of Valencia.

The Asociación Española de la Industria Eléctrica (UNESA, Electric Industry Association of Spain) and Almaraz-Trillo NPPs AIE sponsored this work.

FOREWORD

This report represents one of the assessment or application calculations submitted to fulfil the bilateral agreement for cooperation in thermal-hydraulic activities between the Consejo de Seguridad Nuclear (CSN) and the U.S. Nuclear Regulatory Commission (NRC) in the form of a Spanish contribution to the NRC's Code Assessment and Management Program (CAMP), the main purpose of which is to validate the TRAC/RELAP Advanced Computational Engine (TRACE) code.

CSN and the Asociación Española de la Industria Eléctrica (Electric Industry Association of Spain), together with some relevant universities, have established a coordinated framework (CAMP-Spain) with two main objectives: to fulfil the formal CAMP requirements and to improve the quality of the technical support groups that provide services to the Spanish utilities, CSN, research centers, and engineering companies.

The AP-28 Project Coordination Committee has reviewed this report, the contribution of one of the Spanish utilities to the above-mentioned CAMP-Spain program, for submission to CSN.

UNESA
December 2009

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EXECUTIVE SUMMARY

In this report is presented the methodology developed to improve a RELAP5 full plant model of Trillo NPP (Trillo Plant Analyzer - APT) with a coupled PARCS 3-D core.

The driving force for this development was a plant cooling transient occurred in year 2000. That transient resulted in an axial power profile deformation that was not possible to model with the RELAP point-kinetic (0-D) core. The improved RELAP/PARCS plant model behaviour is validated against those real cooling transient records.

The Trillo NPP is the only German design reactor in Spain. It is a three loop PWR of former KWU design, with a nominal core power of 3010 megawatts thermal, in commercial operation since 1988.

Trillo NPP, as the rest of the German plants, has sophisticated automatic systems, including the control, protection, but specially the limitation system. This limitation system, that takes automatic actions with priority over operators, has a circuit of in-core surveillance that limits the reactor power by changes of the power axial profile.

All these automatic systems are simulated in detail with RELAP modules in APT. To reproduce a plant transient with RELAP/PARCS, it was necessary to modify the coupling capabilities in order to transfer the control rod position and the boron content from RELAP to PARCS, and the in-core measurements from PARCS to RELAP.

As a result of this assessment, the methodology, modifications and tools to run coupled RELAP/PARCS full plant model calculations on Trillo NPP is well established. The almost perfect comparison with the real plant data, gives us the confidence of the adequacy of the model for future applications.

It is worthy to mention that this first long term simulation (1000 sec), with the very complete plant model of RELAP coupled to a relatively large core model with PARCS, required almost 50 times the CPU time required for the point kinetics model.

ABBREVIATIONS

PWR	Pressurized Water Reactor
CAMP	Code Assessment and Management Program
APT	Trillo Plant Analyzer
APT-3D	Trillo Plant Analyzer with PARCS 3D core.
CSN	Consejo de Seguridad Nuclear (Spanish Nuclear Regulatory Council)
RELAP	Reaction Excursion and Leak Analysis Program
TRACE	TRAC/RELAP Advanced Computational Engine
CNAT	Almaraz-Trillo NPPs AIE
UPV	Universitat Politècnica de València
IB	Iberdrola Ingeniería
PDD	Power Density Detector.
FA	Fuel Assembly
PARCS	Purdue Advance Reactor Core Simulator
RCP	Reactor Coolant Pump
YR	Control System
YT	Limitation System
YZ	Protection System
FW	Feedwater
PO	Maximum Linear Heat Generation Rate Top of the Core
PU	Maximum Linear Heat Generation Rate Bottom of the Core
CPU	central processing unit
PIPE	Main Hydraulic component of RELAP
HS	Heat Structure component of RELAP
MTC	Moderator Temperature Coefficient
FTC	Fuel Temperature Coefficient (Doppler)

1. INTRODUCTION

One of the most important goals, if not the main objective, which focuses the work of Thermo-Hydraulic (TH) section within the Fuel Department of Almaraz-Trillo NPPs (CNAT), is to understand and reproduce the dynamic behaviour of Almaraz and Trillo NPPs. This objective has led us to the development and daily use of advanced thermal-hydraulic simulation tools. These tools, with more than 20 years of development work, include numerical simulation models and graphical interfaces for both plants.

The base tool for the developments of Almaraz Plant Analyzer (APA) and Trillo Plant Analyzer (APT[3]) is the RELAP5 code [1], currently at version mod.3.3.

Among the lines of work opened to expand the simulation capabilities in CNAT, it is worth to highlight the improvement in core simulation using more advanced neutron kinetics tools (PARCS code [2]) than the "0-D" model included by default in RELAP5.

The driving force for this development line, was a Trillo NPP cooling transient occurred in year 2000. That transient resulted in an axial power profile deformation that was not possible to model with the RELAP point-kinetic (0-D) core. The improved RELAP/PARCS plant model (APT-3D) behavior is validated in this report against this real cooling transient.

To build a full plant model (APT) with a coupled core RELAP/PARCS (APT-3D), there were needed several steps done in collaboration with the UPV and IB:

- Transfer CASMO/SIMULATE model calculations of Trillo to a PARCS model (SIMTAB method).
- Partial core model with RELAP/PARCS.
- Modifications in RELAP / PARCS to allow movement of the control rods in PARCS from RELAP.
- Modifications in RELAP / PARCS to allow boron changes in PARCS from RELAP.
- Replacement of a simplified core (0-D) in the full plant model (APT) for a coupled 3-D core.
- Adjustments of steady-state RELAP/PARCS to CASMO/SIMULATE.
- Power density detectors (PDDs) calibration.

The Trillo NPP is particularly conducive to the use of advanced methods for core simulation because it has two characteristics that make it unique within the Spanish nuclear power fleet:

1. It has in-core on-line instrumentation, Power Density Detectors (PDDs) that generates automatic actions through the system of limitation (YT).
2. The limitation system design prevents the reactor trip during relevant transients like a single RCP trip or a turbine trip, stabilizing the plant to a partial power in a few seconds.

This report summarizes the first assessment of the Trillo plant APT-3D model against a real cooling transient occurred in year 2000. The initial reproduction of this transient with RELAP model (APT-0D) led to develop in 2001 of the simplified module [yq], to approximate the deformation of the axial power profile that was the cause of the activation of the peak power limits (PU) system and the power reduction to 90%. This coupled RELAP / PARCS simulation reproduces the 3-D neutron flux deformation in PARCS with the control rod insertion and the boron injection ordered by RELAP.

2. PLANT DESCRIPTION

The Almaraz and Trillo NPPs are owned by different shareholders (Iberdrola Generación SA, Endesa Generación SA, Gas Natural SDG, Hidroeléctrica del Cantábrico, and Nuclenor S.A.), and operated by Almaraz-Trillo NPPs AIE (CNAT).

The current relevant characteristics of Almaraz and Trillo NPPs are summarized in the following table:

Table 1. Main characteristics of Almaraz and Trillo NPPs.

PLANT PARAMETERS	ALMARAZ	TRILLO
Number of Units	2	1
Design NSSS	Westinghouse	KWU-Siemens
Coolant Loops	3	3
Thermal Power (Mwt)	2947 | 2729	3010
Gross Electrical Power (Mwe)	1050 | 980	1066
Net Electrical Power (Mwe)	1013 | 946	1002
Cycle Length (months)	18	12
Refrigeration System	Cooling Pond	Cooling Towers
Commercial Operation Since	1981 | 1983	1988

The Trillo NPP is the only German design reactor in Spain. It is a three loop PWR of former KWU design, with a nominal core power of 3010 megawatts thermal, in commercial operation since 1988.

There are two main differences between Trillo and Almaraz design. The first one is the great number of systems / equipment of Trillo compared with Almaraz. Despite of the fact than both are three loop plants, Trillo has four redundancies in safeguard systems (safety injection, emergency power, emergency feedwater).

The second difference is that Trillo, as the rest of the German design plants, has sophisticated automatic systems, including the control (YR), protection (YZ), but specially the limitation system (YT). This limitation system, that takes automatic actions with priority over operators, has a specific circuit of in-core surveillance that can reduce the reactor power, for example by deformations of the power axial profile.

The core layout of Trillo (177 FAs) is represented in the next figure. The Power Density Detectors (PDD or LVD in German) performs the surveillance of the neutron flux in 6 positions of the core with 6 different axial levels (36 detectors). The maximum of the three upper levels (PO) and the three lower levels (PU) are compared against calculated limit values.

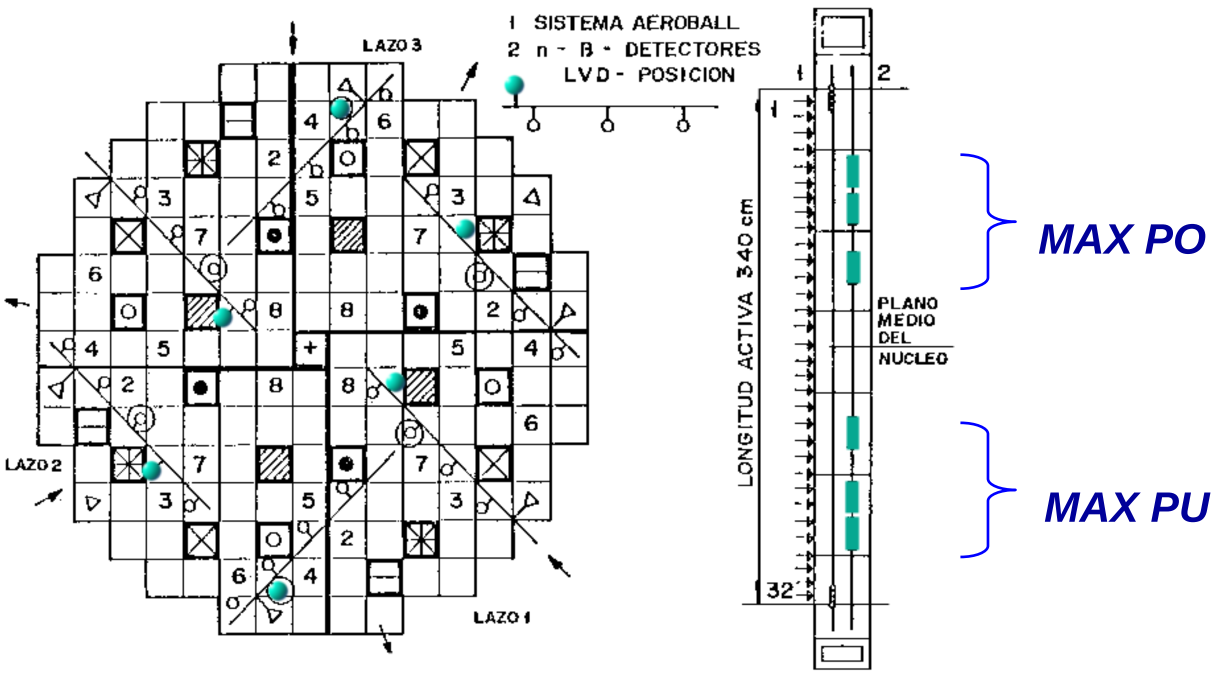

Fig. 1. Trillo Core Layout. Control Rods and PDDs location.

3. TRILLO PLANT ANALYZER (APT)

The Trillo NPP simulation with RELAP5 started in 1988 with the start-up tests simulation. The RELAP5 numerical model has grown over the years with the different plant applications (i.e. NUREG/IA-0177 [7], operator training, real plant analysis, safety analysis, PSA scenarios, etc.) up to the current model scope.

The thermo-hydraulic and I&C simulations includes:

- The primary circuit (Fig. 2):
  - Vessel with a triple downcomer and two channel core, point kinetic core.
  - Detailed loops and RCPs
  - Pressurizer with pressurizer relief tank, spray lines, heaters.
  - Auxiliary Systems: Volumetric and chemistry control
  - Safeguard Systems: Safety Injection (High Pressure, Low Pressure, Accumulators), Extra Borating System.
  - Detailed Steam Generators (tube-side)

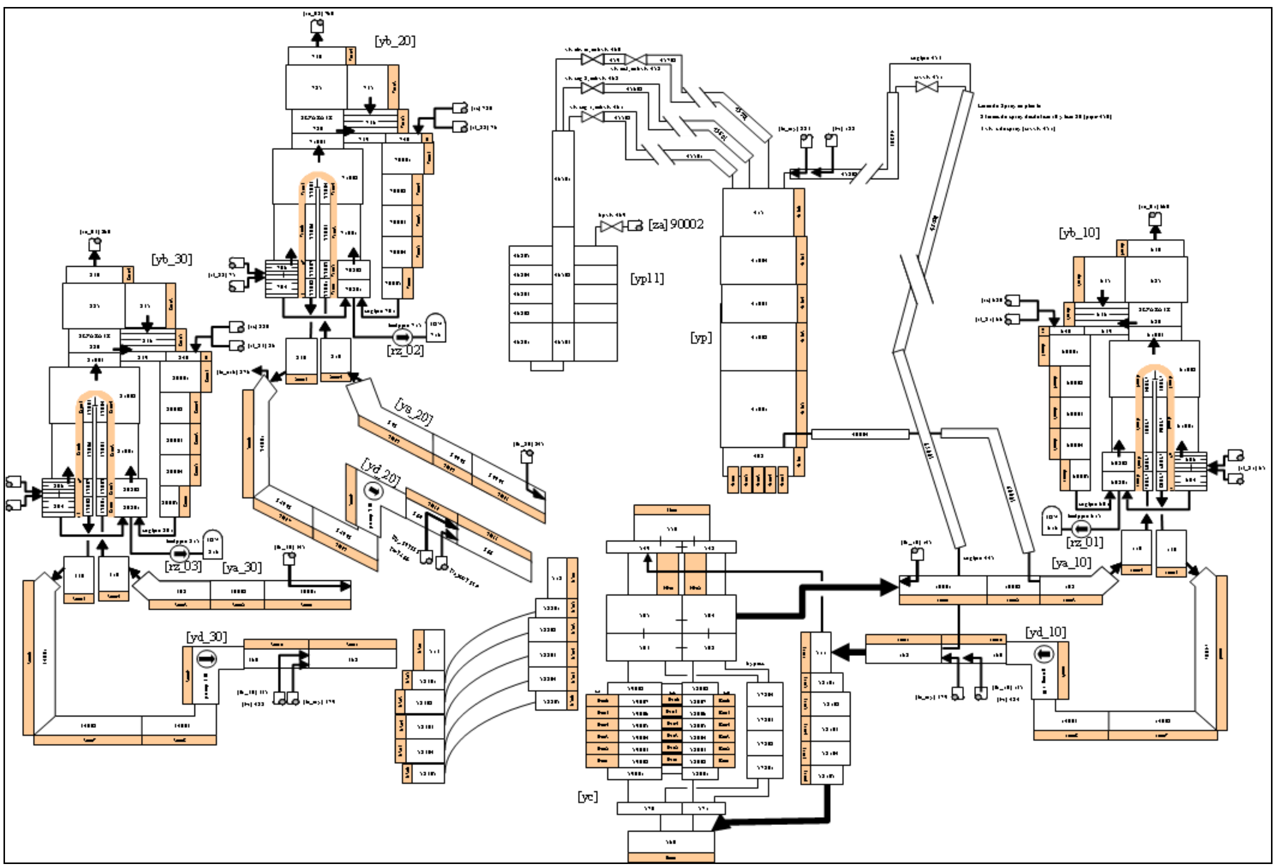

Fig. 2. Trillo Primary Circuit Model with RELAP5.

- The secondary circuit: (Fig. 3)
  - Detailed Steam Generators (shell side)
  - Feedwater system (from the feedwater tank to SGs, including both heating trains and the start-up feedwater system).
  - Main Steam System (relief and safety valve stations)
  - Main turbine and turbine bypass systems
  - Safeguard Systems: Emergency feedwater system.

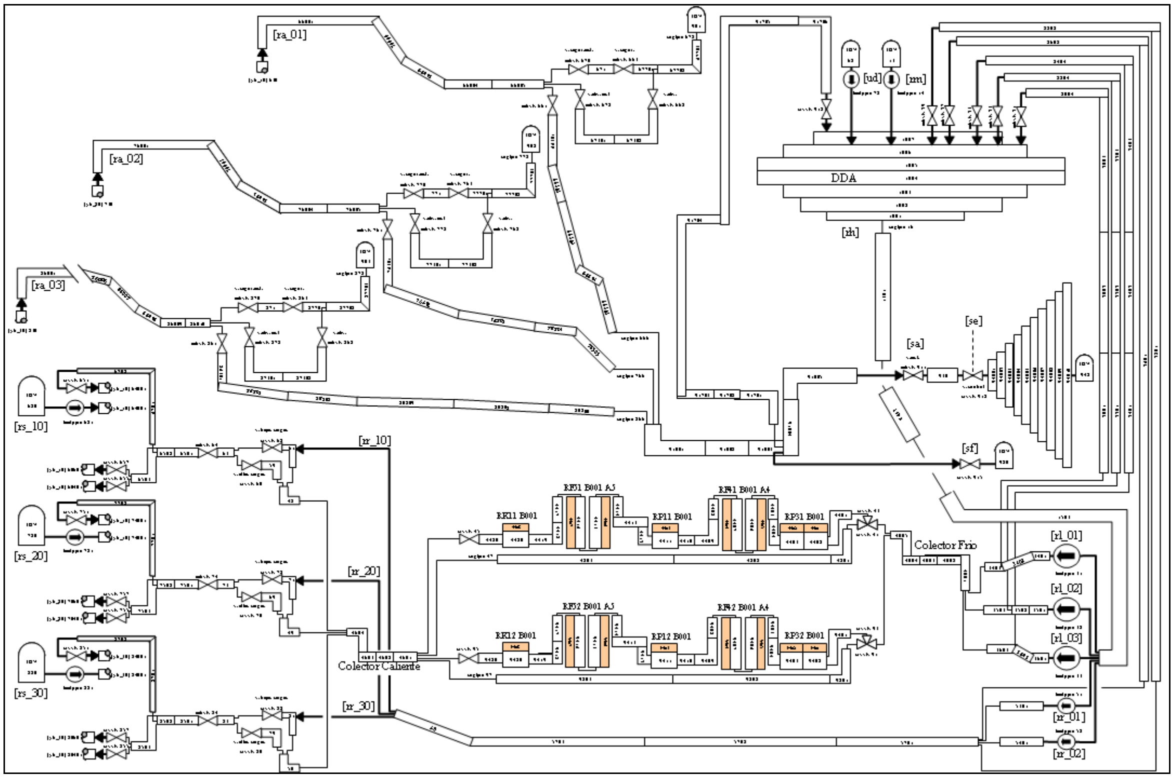

Fig. 3. Trillo Secondary Circuit Model with RELAP5.

- The I&C simulation includes:
  - Control, Protection and Limitation Systems
  - Steam Generators Level control.
  - Control loops and functional groups.

The RELAP5 numerical model has been improved with a graphical and interactive simulation performed by means of CSV [5] / NPA [6] software. Based on our simulation needs, several modifications were performed to this numeric / graphic coupling, allowed us to spread the use of the Plant Analyzers among the organization.

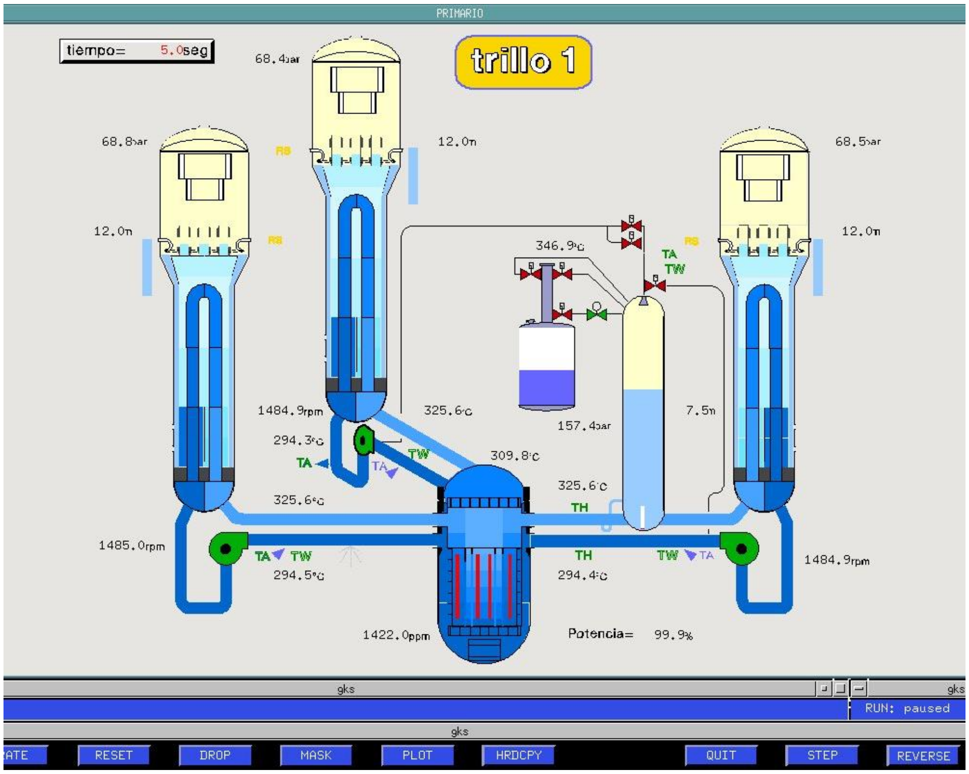

Fig. 4. APT Screen. Primary Circuit.

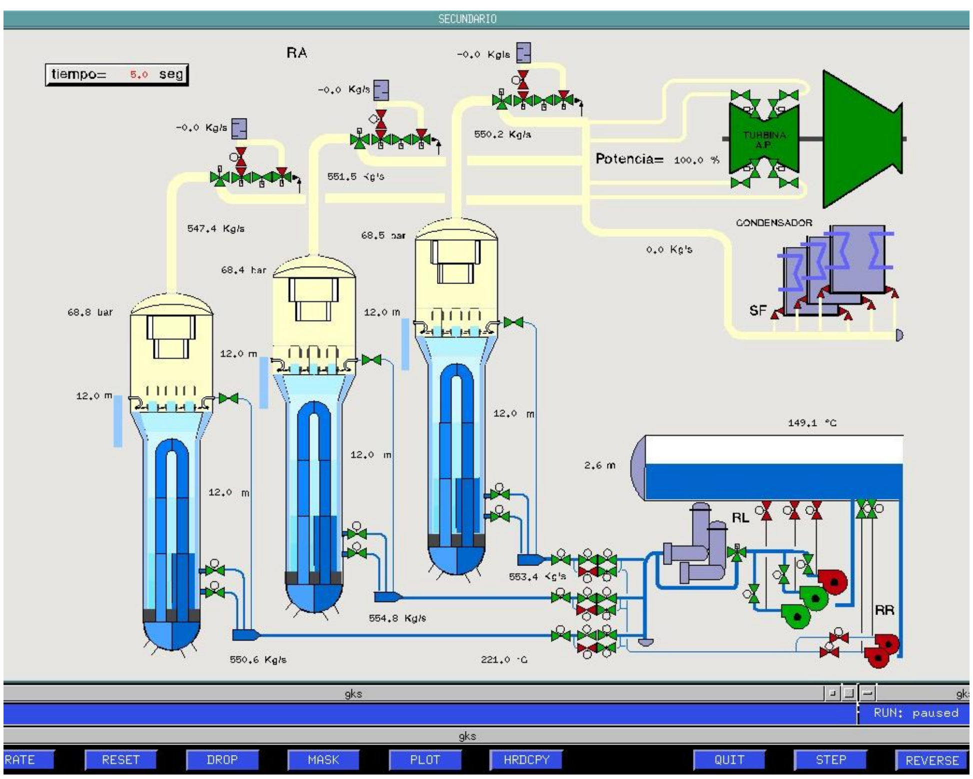

Fig. 5. APT Screen. Secondary Circuit.

4. METHODOLOGY FOR 3-D PLANT MODEL CONFIGURATION

The calculation methodology is based on running parallel simulations, thermo-hydraulics (RELAP5) and neutronics (PARCS). For this parallel runs, with coordination of time steps of both codes, the "Parallel Virtual Machine" PVM [4] is used.

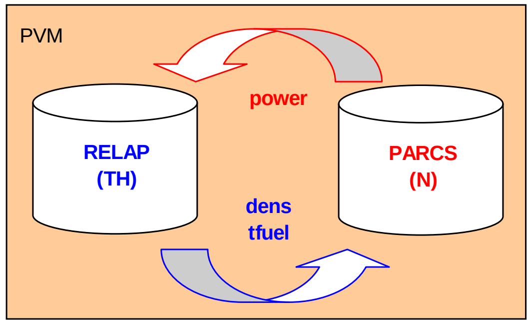

Fig. 6. Parallel execution scheme RELAP/PARCS.

The diagram above indicates the standard variables sent from RELAP each time step (moderator density and fuel temperature), for PARCS to calculate the distribution of netron flux with the cross sections tabulated in terms of these variables. The power of each node in the core is transferred to the heat structures simulating the fuel elements in RELAP.

However for the application on whole plant models it has been necessary to modify the calculation scheme to introduce the effect in PARCS of the control rod movement and the boron content calculated in RELAP:

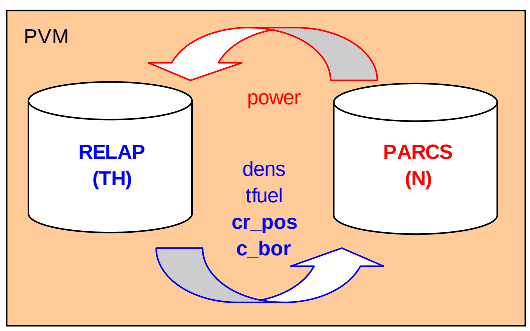

Fig. 7. Modified parallel execution scheme RELAP/PARCS.

The first modification of the coupling scheme allows the transfer of RELAP control variables that specify in PARCS the positions of the control rods. This change is essential to reproduce plant transients, where the RELAP model simulates these positions based on orders from the automatic systems of control, limitation and protection.

The second modification allows the transfer of RELAP boron density in each of the core volumes, to be used in PARCS as a value of interpolation between two sets of cross sections at different boron concentrations.

Before running a coupled calculation of a plant transient, it is necessary to perform a series of steps to get a properly configuration of PARCS and RELAP models and their link:

Models Configuration Steps:

1. CASMO / SIMULATE: Core 3D simulation with representative cross sections of the burning conditions of the day of the event.
2. SIMTAB: Collapsation of the cross sections for use in PARCS.
3. PARCS: Generation of input file to PARCS - steady state / transient. Neutron model.
4. RELAP: Generation of input file to RELAP - steady state / transient. TH model.
5. MAPTAB: Generation of tabular map of correspondence between TH channels (RELAP) and neutronic compositions (PARCS).

Simulation Steps:

6. PARCS steady-state alone calculation. (P_SSA).
7. RELAP steady-state alone calculation. (R_SSA).
8. Coupled steady-state simulation. (_CSS).
9. Coupled transient calculation. (_CTR).

Three tools have been developed for automatic input file generation (RELAP5, PARCS) and mapping method between both codes (MAPTAB).

4.1 CASMO / SIMULATE

In collaboration with Iberdrola Ingeniería (IB), the Fuel Department of CNAT has developed 3-D neutronic models of Almaraz and Trillo cores with CASMO-4/SIMULATE-3. These models are validated every cycle against the core neutron flux maps in both plants, through the simulation of burnup history of the core.

From a geometric mesh of the core, CASMO-4/SIMULATE-3 models calculate the neutron cross sections and three-dimensional neutronic parameters that characterize the steady state with a given position of the control rods.

The CASMO / SIMULATE output files, with a high number of "neutronic compositions" or types of cells with different cross sections due to fission products obtained as a result of burning the fuel, are used as starting point for the development of PARCS neutronic 3-D model.

The CASMO / SIMULATE model of Trillo used for this application includes 178 channels (177 FAs + 1 radial reflector), with 32 axial levels in the active zone plus two axial levels for the lower and upper axial reflectors.

Besides the cross-sections, the output files of CASMO / SIMULATE contain geometric information and boundary conditions that are used in the automatic generating of the RELAP and PARCS models.

4.2 SIMTAB

The objective of SIMTAB methodology (developed by UPV) is to reduce the number of "compositions" calculated with CASMO / SIMULATE and transform them in tabular format for use in PARCS or other neutronic codes.

The method of reducing the number of compositions is based on grouping them in different burnup intervals (ΔB), i.e. the compositions of CASMO / SIMULATE differentiated less than ΔB in steady state are represented by a single composition in PARCS model.

- In this application a burning discrimination of $\Delta B = 0.1$ GWd / TU have been used. The 177 FAs have been reduced in PARCS to 36 different FAs.

Other important parameters for the generation of the cross sections files in PARCS, are the expected ranges of variation of their basic parameters (moderator density, fuel temperature) during the transient of interest. If during the transient these ranges of variation are exceeded, it would be necessary to recalculate the collapsed cross sections.

- For this application wide ranges of density (222 to 914 kg/m3) and fuel temperature (422 to 1300 º C) have been used.

The outcomes of this method are the tabulated cross section files NEMTAB (without control rod “unroded”) and NEMTABR (with control rod “roded”).

- For this application two sets of tables at two the boron concentrations that cover the range of variation during the transient:
  - NEMTAB_639ppm / NEMTABR_639ppm.
  - NEMTAB_1000ppm / NEMTABR_1000ppm.

4.3 PARCS

PARCS is the acronym for "Purdue Advance Reactor Core Simulator." This 3-D neutronic code is distributed by the NRC for its coupling with the latest versions of the thermal-hydraulic code RELAP and TRACE.

The most important feature of PARCS is that it can be used to simulate steady state operation and transient resulting from reactivity disturbances. The code solves the diffusion equation for two groups of neutrons in 3-D geometry and with temporal dependency.

The PARCS input deck represents the core configuration in one burnup point, the burning of the core model during the operation of the cycle is performed by other codes like CASMO / SIMULATE. The most relevant input data are the geometric information, the cross sections and the initial and boundary conditions. These three pieces of input are prepared in independent files and automatically generated from the SIMULATE output files.

For this application, the 36 different FAs (“radial.mapN” see next figure) obtained with SIMTAB, plus the radial reflector, are subdivided in 32 + 2 axial levels.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	0	0	0	0	0	37	37	37	37	37	37	37	0	0	0	0	0
2	0	0	0	37	37	37	11	9	10	8	6	37	37	37	0	0	0
3	0	0	37	37	8	1	12	13	13	13	12	5	10	37	37	0	0
4	0	37	37	11	2	14	21	34	4	33	21	14	2	10	37	37	0
5	0	37	9	2	28	36	20	17	19	18	19	35	28	2	10	37	0
6	37	37	5	14	35	16	30	17	22	17	31	16	35	14	1	37	37
7	37	7	12	21	19	31	25	26	23	26	25	29	20	21	12	11	37
8	37	8	13	33	18	17	26	15	32	15	26	17	17	34	13	8	37
9	37	10	13	4	19	22	24	32	3	32	23	22	19	4	13	11	37
10	37	8	13	34	17	17	27	15	32	15	26	17	18	33	13	8	37
11	37	11	12	21	20	30	25	26	23	26	25	31	19	21	12	6	37
12	37	37	1	14	36	16	31	17	22	17	29	16	35	14	5	37	37
13	0	37	8	2	28	36	19	18	19	17	20	36	28	2	10	37	0
14	0	37	37	11	2	14	21	33	4	34	21	14	2	11	37	37	0
15	0	0	37	37	10	5	12	13	13	13	12	1	9	37	37	0	0
16	0	0	0	37	37	37	7	9	11	8	10	37	37	37	0	0	0
17	0	0	0	0	0	37	37	37	37	37	37	37	0	0	0	0	0

Fig. 8. PARCS Neutronic Radial Map. "radial.mapN"

4.4 RELAP

The RELAP model used for the Trillo Plant Analyzer (APT) is modified in three aspects:

- **Hydraulic**: replace the simplified APT core with two axial channels and a bypass by a chosen number of channels in parallel.
- **Thermal**: replace the simplified APT core with two heat structures representing the fuel rods cooled for each of the hydraulic channels to a number of chosen heat structures and coupled to the PARCS neutronic calculation.
- **Automatic**: replace the simplified module [yq] used to approximate the deformation of the axial profile, by the direct reading of the linear power structures that represent the ECs with PDDs.

To create a core model with component numbers compatible with the numbering of the rest of APT model, a specific program has been developed. For this purpose the program reads:

- Two radial maps, one Hydraulic and one Thermal to obtain the component numbering.
- The geometric information from SIMULATE output files.
- The initial conditions from SIMULATE output files.

For the present application the 36 different FAs of the neutronic map (Fig. 8) has been extended to 42 to represent specifically the 6 FAs that house the core instrumentation lances PDDs (Fig. 1). In this way the 3-D RELAP core is formed with 42 hydraulic and 42 thermal channels.

In the radial hydraulic map the 42+1 channels (PIPE components) are defined (see next figure), with the same axial division 32+2 levels used in CASMO / SIMULATE and PARCS.

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
						578	578	578	578	578	578	578					
P				578	578	578	192	190	191	177	175	578	578	578			
O			578	578	177	170	193	194	194	388	193	174	191	578	578		
N		578	578	192	171	195	273	374	173	373	273	195	171	191	578	578	
M		578	190	171	297	387	272	198	271	199	271	386	297	171	191	578	
L	578	578	174	195	386	197	299	198	274	198	371	197	391	195	170	578	578
K	578	176	193	273	271	371	293	294	291	294	293	298	272	273	193	192	578
I	578	177	194	373	199	198	389	196	372	196	294	198	198	374	194	177	578
H	578	191	194	173	271	274	292	372	172	372	291	274	271	173	194	192	578
G	578	177	194	374	198	198	296	196	372	196	392	198	199	373	194	177	578
F	578	192	193	273	272	299	293	294	291	294	293	371	271	273	193	175	578
E	578	578	170	195	390	197	371	198	274	198	298	197	386	195	174	578	578
D		578	177	171	297	387	271	199	271	198	272	387	297	171	191	578	
C		578	578	192	171	195	273	373	173	374	273	195	171	192	578	578	
B			578	578	191	174	193	393	194	194	193	170	190	578	578		
A				578	578	578	176	190	192	177	191	578	578	578			
						578	578	578	578	578	578	578					

Fig. 9. RELAP Hydraulic Radial Map. “radial.mapH”

In the radial thermal map the 42+1 Heat Structures are defined (see next figure), with the same axial division 32+2 levels used in CASMO / SIMULATE and PARCS.

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
						578	578	578	578	578	578	578					
P				578	578	578	861	859	860	858	856	578	578	578			
O			578	578	858	851	912	913	913	751	912	855	860	578	578		
N		578	578	861	902	914	921	934	904	933	921	914	902	860	578	578	
M		578	859	902	928	936	920	917	919	918	919	935	928	902	860	578	
L	578	578	855	914	935	916	930	917	922	917	931	916	754	914	851	578	578
K	578	857	912	921	919	931	925	926	923	926	925	929	920	921	912	861	578
I	578	858	913	933	918	917	752	915	932	915	926	917	917	934	913	858	578
H	578	860	913	904	919	922	924	932	903	932	923	922	919	904	913	861	578
G	578	858	913	934	917	917	927	915	932	915	755	917	918	933	913	858	578
F	578	861	912	921	920	930	925	926	923	926	925	931	919	921	912	856	578
E	578	578	851	914	753	916	931	917	922	917	929	916	935	914	855	578	578
D		578	858	902	928	936	919	918	919	917	920	936	928	902	860	578	
C		578	578	861	902	914	921	933	904	934	921	914	902	861	578	578	
B			578	578	860	855	912	756	913	913	912	851	859	578	578		
A				578	578	578	857	859	861	858	860	578	578	578			
						578	578	578	578	578	578	578					

Fig. 10. RELAP Thermal Radial Map. “radial.mapT”

The grey channels (PIPE-578 and HS-578) represent the core bypass (coupled to the radial reflector). The yellow and pink channels correspond to the outer and inner channels in the 0-D core model. The 6 light blue channels (PIPE and HS) are the FAs channels with PDD instrumentation.

The total number of PIPE volumes and HS in this new 3-D core is 1462 each.

Note that it is not necessary to use the same number of hydraulic than thermal channels. In fact it was tested a core model with 2 PIPES and 42 HS, obtaining quite similar steady-state results than the 42/42 configuration.

4.5 MAPTAB

The parallel calculation process of RELAP / PARCS requires a "mapping" between the RELAP hydraulic and thermal components and the PARCS neutron nodes. In this way the transfer of thermal-hydraulic information (moderator density, fuel temperature, and boron concentration) in one direction and the power in the other, is performed.

This tabular map is defined in “MapTab” file, automatically generated with a specific program that reads the “radial.mapN”, “radial.mapH” and “radial.mapT”.

The modification of the control rod position transfer is also specified in the same “MapTab” file by defining the RELAP control variables that simulate the different control rod positions.

- For this application each control rod bank D (4 CRs) has been divided in two semi-banks that moves simultaneously. For example the bank D10 is represented by semi-banks 1 and 2. In the next figure the D10 to D60 banks are represented in colour.

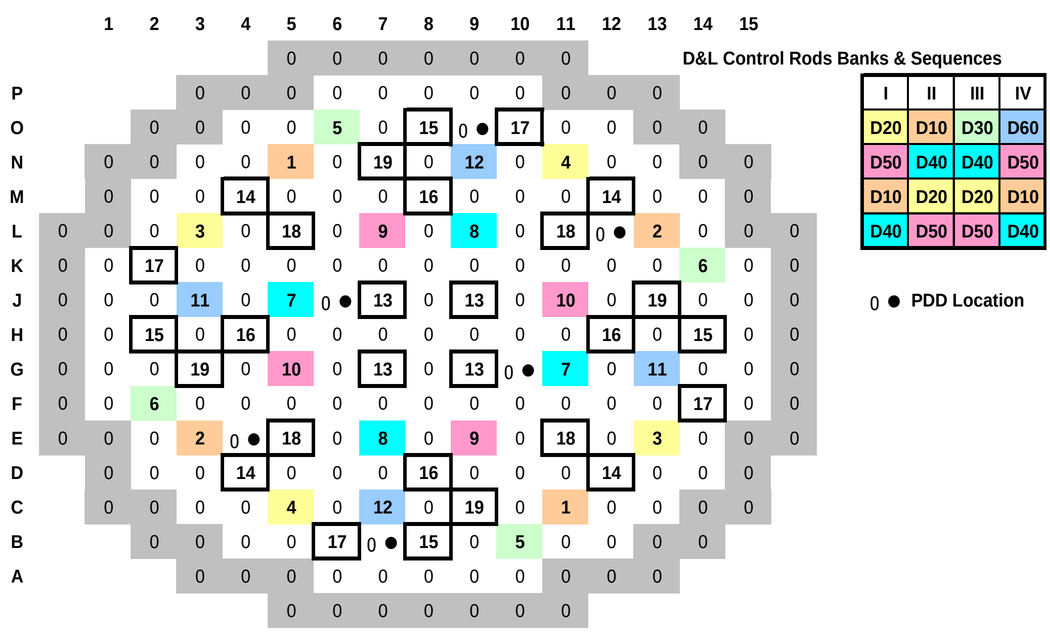

Fig. 11. PARCS Control Rod Simulation.

There are four different sequences of control bank insertion (I to IV in Fig. 11). In the date of the analyzed transient the sequence IV was active in the plant, that is the bank 1-D corresponds to D60, 2-D to D50, 3-D to D10, and 4-D to D40.

4.6 PARCS Steady-State Alone calculation (P_SSA).

The first step after the generation of the PARCs input file is to perform single steady-state run of PARCS to compare with the reference case of CASMO/SIMULATE. The steady-state calculation is perform with the additional files and conditions:

- Geometrical information “GEOM_LWR”.
- Cross sections NEMTAB and NEMTABR at the SIMULATE boron concentration.
- Fixed thermal-hydraulic boundary conditions (density and fuel temperatures from SIMULATE).
- Static position of control rods.

The calculated solution of PARCS is compared in terms Keff and axial power profile with the one obtained by CASMO / SIMULATE. In the following figure, the average core axial profile of SIMUATE is compare with two PARCS calculations, one with CRs in the same positions of SIMULATE and the other with the active sequence IV.

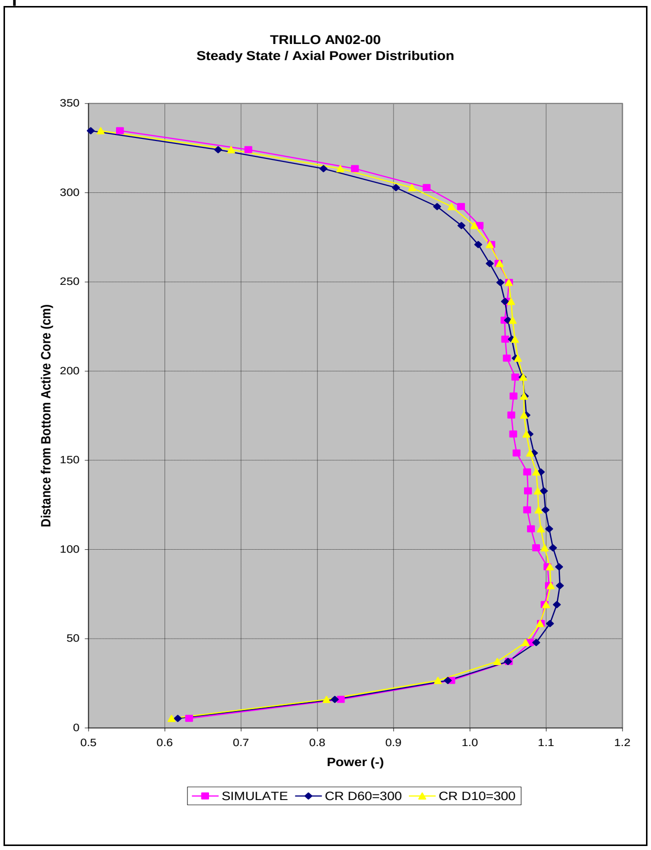

Fig. 12. PARCS Steady-state Alone Comparison.

The first case reproduced is well adjusted, while the second (with the real control bank sequence) is a little more bottom peaked.

4.7 RELAP Steady-State Alone calculation (R_SSA).

Once the simplified TH core simulation of APT-0D (2 PIPEs / 3 HSs) is replaced by the complex 3-D core (42 PIPEs / 42 HSs), a null transient is performed to reach the stable initial conditions for the full plant model. For this calculation the reactor power is fixed to 100% (3010 Mwth), with a distribution over the HSs obtained from the SIMULATE reference case.

The RELAP steady-state alone calculation with APT-3D is compared against the same calculation APT-0D to check the primary variables, specially the mass flow rate distribution in the primary circuit, core, and bypass.

<u>PDDs calibration</u>

The linear power values in the FAs of the positions occupied by PDDs will be used as input measurement of the limitation system YQ. Each one of the 36 detectors surveys a region of the core. With the linear heat generation rate (LHGR) of each one of the 177 FAs in SIMULATE 3D model, the maximum value of each surveillance region is calculated.

The factor between the maximum linear power calculated for each monitoring area and the calculated value for the FA with PDD, is used as calibration factor YQ system simulation. These calibration factors are applied directly over the calculated RELAP linear power of the FAs with PDD.

The RELAP restart file of this calculation will be used in the next step.

4.8 Coupled steady-state simulation. (_CSS).

This step is quite similar to the usual process of RELAP steady state calculation. The reactor kinetics is activated in the steady-state input as a restart calculation of the previous step. The differences between a typical APT-0D and this APT-3D steady state are:

- Activation of the coupling with PARCS (card 1 in RELAP, and TH feedback in PARCS)
- Change from 0-D power variables to 3-D power in the automatic simulation.
- Change from simplified YQ simulation to full YQ-3D simulation.

The coupled RELAP/PARCS calculation process is performed by running both codes in parallel with PVM and the mapping between TH cells and neutronic nodes defined in MAPTAB file.

The change in the active sequence (IV) of the CRs with respect to SIMULATE configuration does not modify significantly the steady state power distribution in the core, from the previous step.

The restart output files of RELAP and PARCS will be used in the next step.

4.9 Coupled transient calculation. (_CTR).

The last step is the RELAP/PARCS coupled transient calculation. The initial event is simulated in the RELAP input file, and the response of the automatic systems modelled in APT conduct the dynamic evolution of the plant.

The change of the TH conditions in the core, the movement of the control rods or the change in boron concentration calculated with RELAP, modify the solution of the core neutron flux of PARCS, that feedback the power in RELAP HSs and the in-core and ex-core simulated measurement of RELAP.

5. PLANT TRANSIENT DESCRIPTION

The initial event of the transient occurred in Trillo NPP on the 18/10/2000, when the plant was operating at 100% power, was an isolation and bypass of a high pressure feedwater heating train (Fig. 13).

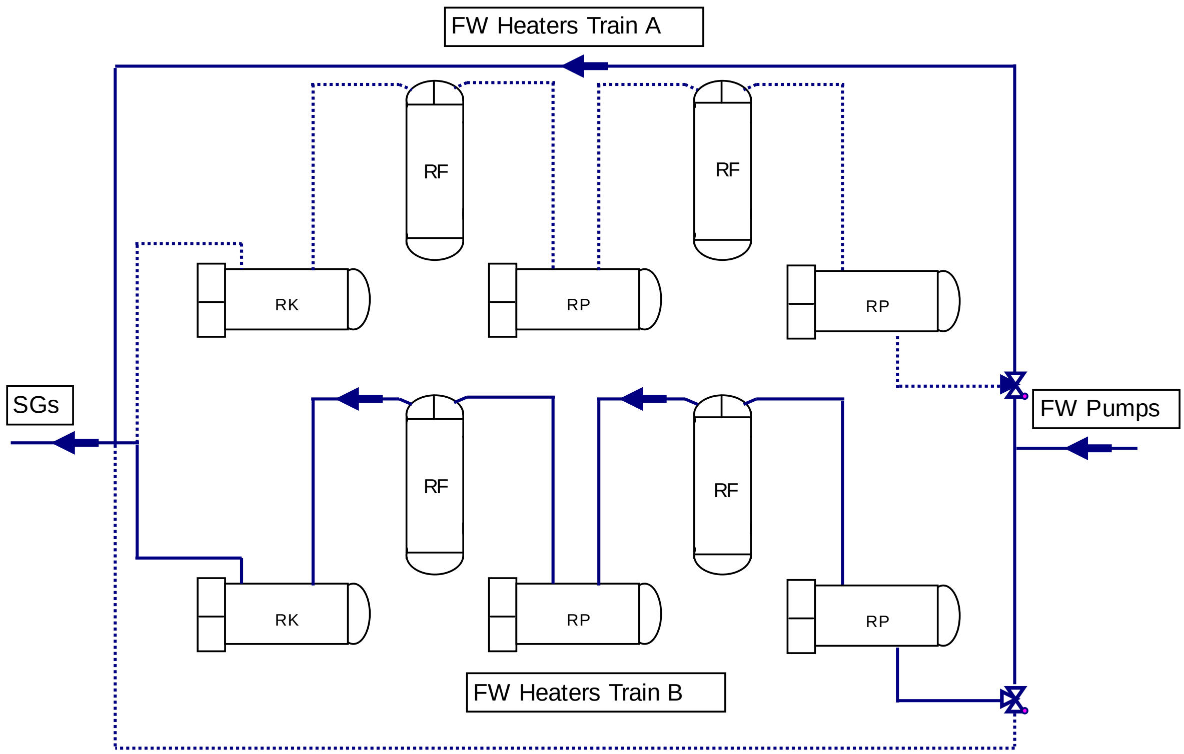

Fig. 13. High Pressure Heating Train Isolation.

The second train remained in operation heating the water that mixed in the feedwater header with the bypassed cold water of the affected train. The reduction of the feedwater temperature produces a cooling down of the primary circuit and the correspondent power increase by the negative Moderator Temperature Coefficient (MTC).

At the date of the transient the cycle was close to its middle point (MOC), so the MTC was big enough to increase the power over the limitation values of total power (L-RELEB), and axial profile deformation (PU-RELEB).

The insertion of control rods limited the increase of the reactor power (PR) over its allowed value (PERL). The negative reactivity of the control rods compensated the positive feedback from the coolant temperature reduction. Depending on the value of this coefficient (function of the cycle burnup), it will be required more or less length control rods insertion.

In the evolution of the transient, the insertion of control rods was important enough to generate boundaries of PU-RELEB (by axial power profile deformation in the lower part of the core) and D-STAFAB (by absolute position of banks). The first was the cause of the reduction of PERL at a rate of 4.5% / min, while the control position of D bank and the limit of STAFAB led to a temporal boration from TB / TA systems.

The reactor power was stabilized at about 84% by the actions of the limitation system, supported by the operator decision of reducing the power demanded in the turbine, that helped the recovery of the average temperature in the primary circuit. At the same time ordered injections of demineralised water to compensate the injected boron.

Subsequently the reactor power was increased up to 100%, reaching a power turbine ~97%.

6. TRANSIENT SIMULATION

The results of the transient calculation introduced in (4.9), are analyzed below in two sections:

- First, the evolution of the relevant plant simulator parameters are compared with plant records (usual validation process).
- Second, the analysis of core behaviour by comparing the simulation versus available records, and 3-D representation of core status and axial profile evolution.

In the following comparison plots, the APT variables are identified with parenthesis in their legends.

6.1 Plant Results

The RELAP input for the transient calculation is exactly the same as the one used for APT-0D. It includes:

- T=10 seconds. Flip the three-way valve RL11S001 to the bypass of heater train RL21 position.
- Simplified reduction of turbine extractions to the isolated heaters.
- Manual turbine power reduction (t > 300 sec)
- Manual orders of demineralised water injection (t > 545 sec)

The feedwater temperature reduction and the main steam pressure evolution have a direct influence in the primary cold legs temperatures.

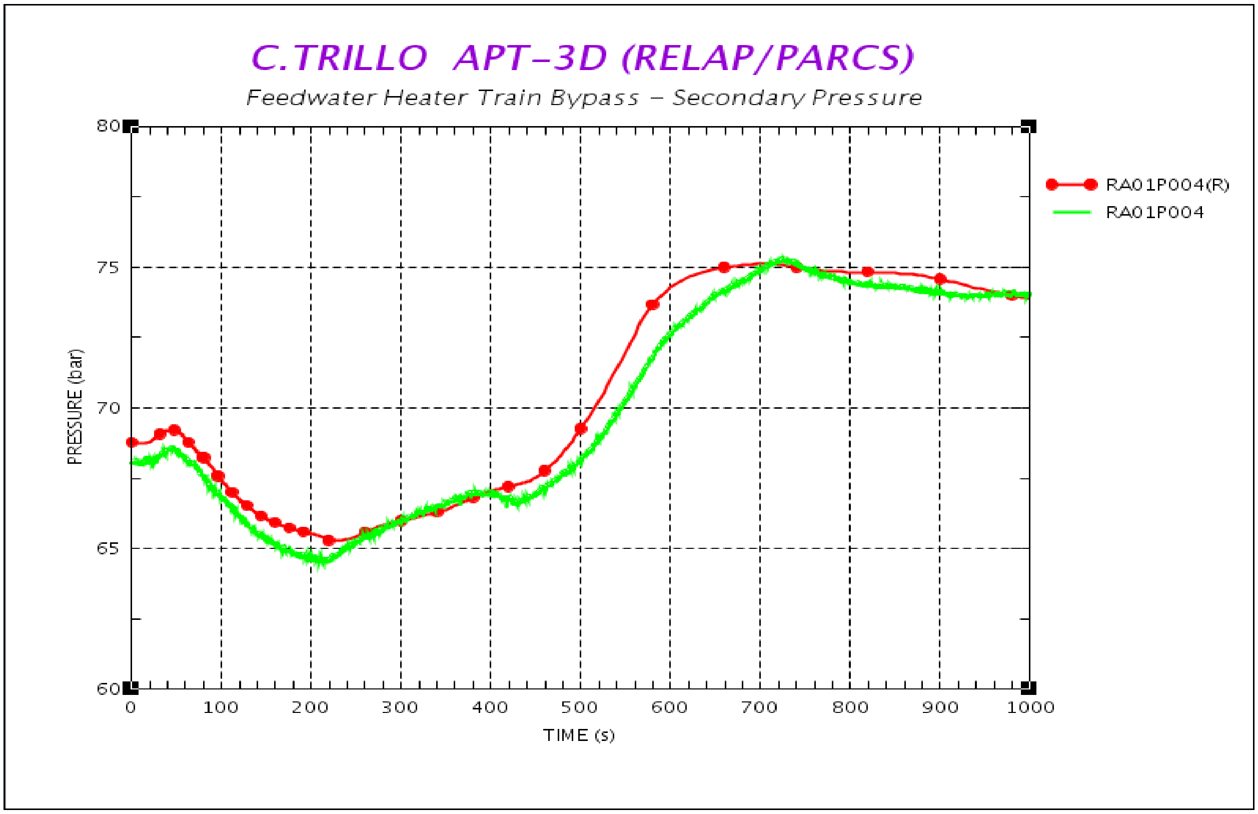

Fig. 14. Main Steam Pressure (Loop-1).

As it can be seen in (Fig. 14) and (Fig. 15) APT-3D correctly reproduces the initial reduction of steam pressure and cold leg temperatures, and the posterior increase due to the turbine power reduction.

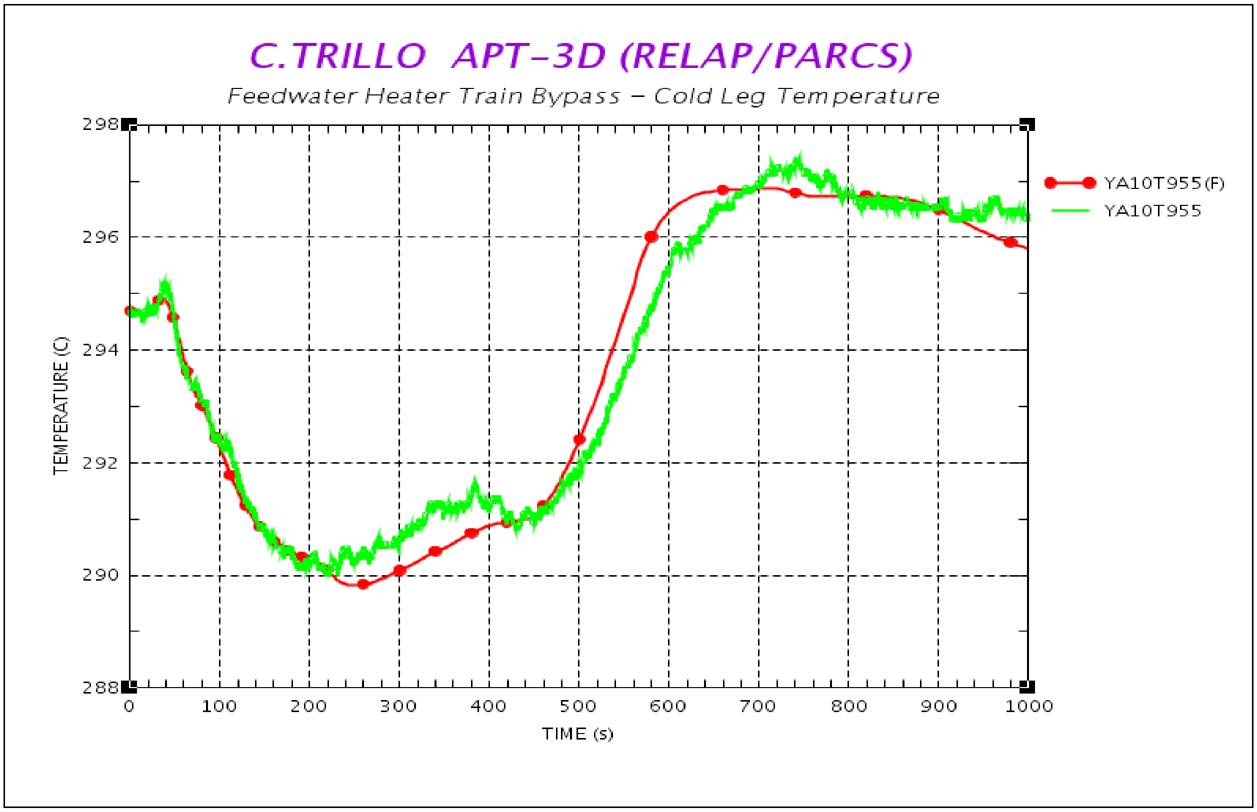

Fig. 15. Cold Leg Temperature (Loop-1).

With the correct simulation of the cold leg temperature conditions, the coupled model simulates the increase in power and the automatic bank insertion order by the limitation system (YT). First 1-D and L banks in parallel and second 1-D alone after reaching the first limit of the axial power profile deformation in the lower part PU-RELEB.

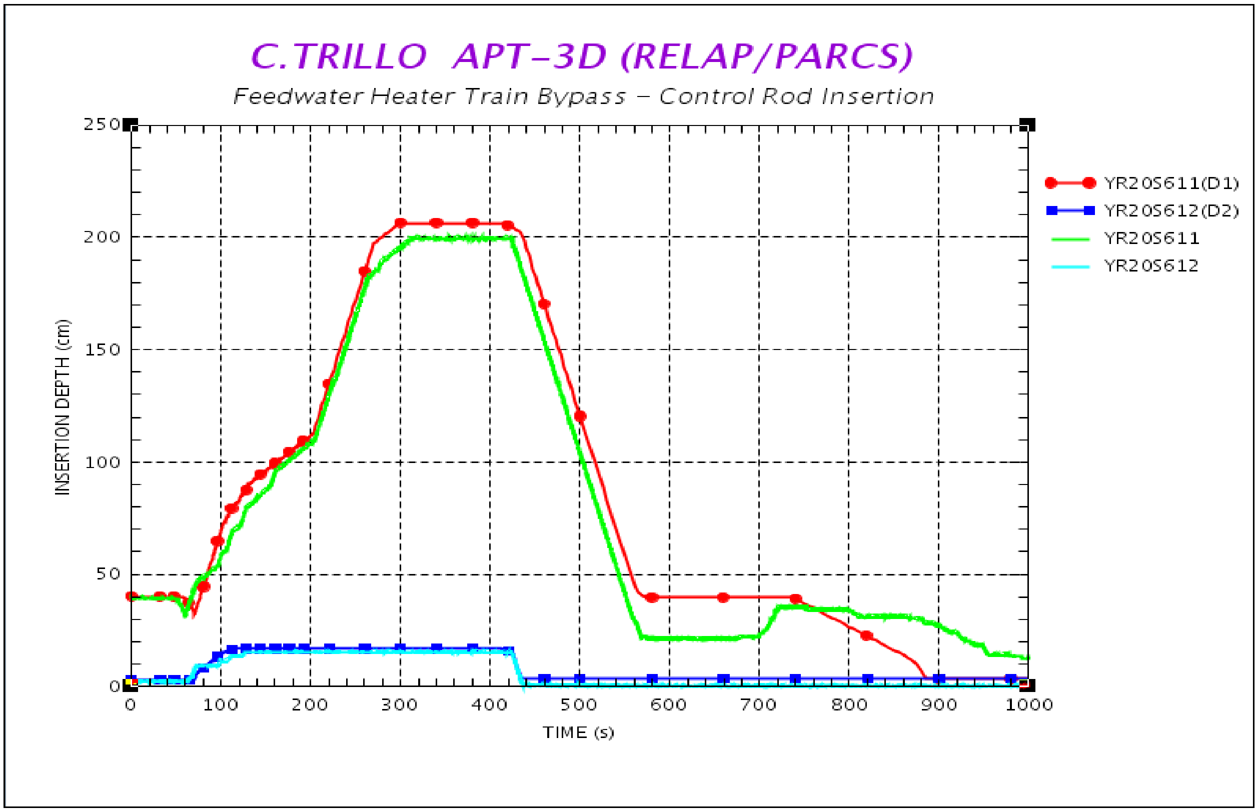

Fig. 16. Control rod Banks Insertion Depth (1D, 2D).

The allowed reactor power (PERL) is automatically reduced when the second limit of PU-RELEB is reached. The total reactor power (PKG) is reduced to follow the allowed value by continuous 1-D bank insertion.

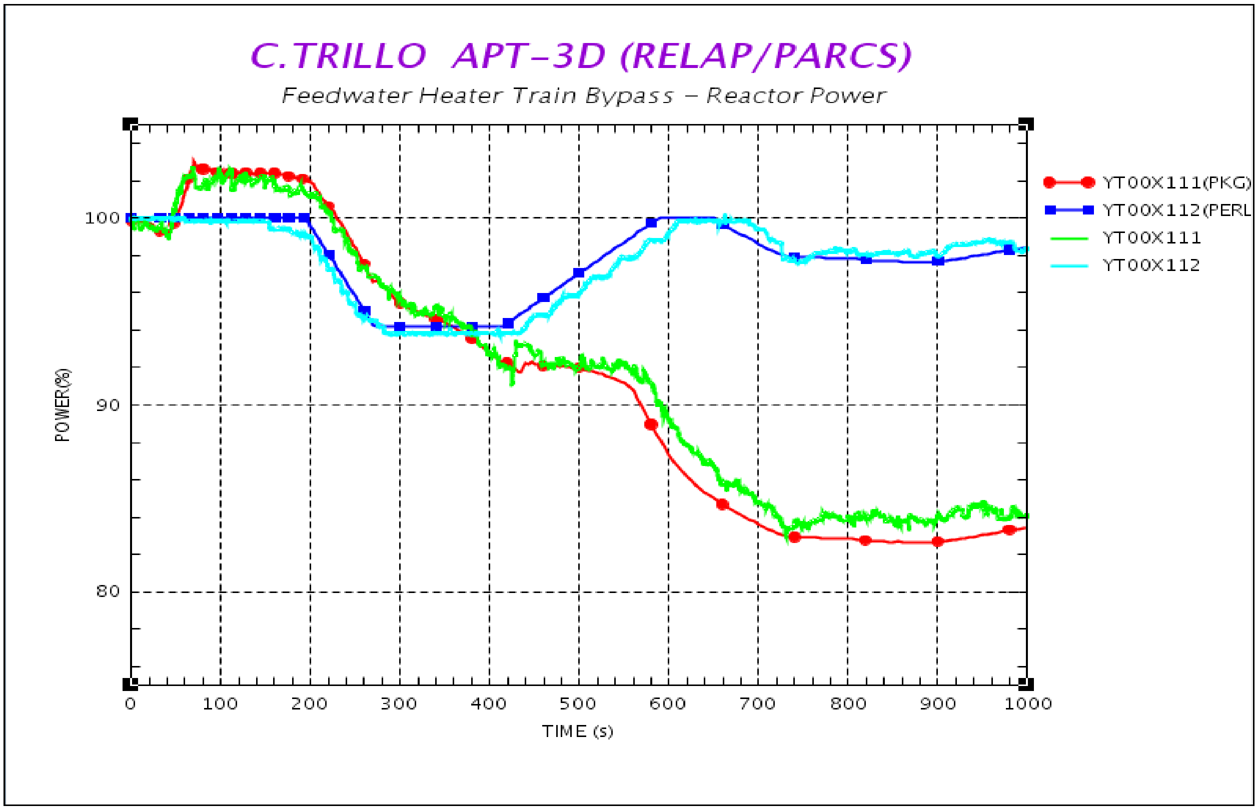

Fig. 17. Reactor Power (PKG) and Allowed Power (PERL).

The additional 1-D insertion reaches one of the bank insertion limits (D-STAFAB) that automatically activate the temporal injection of borated water.

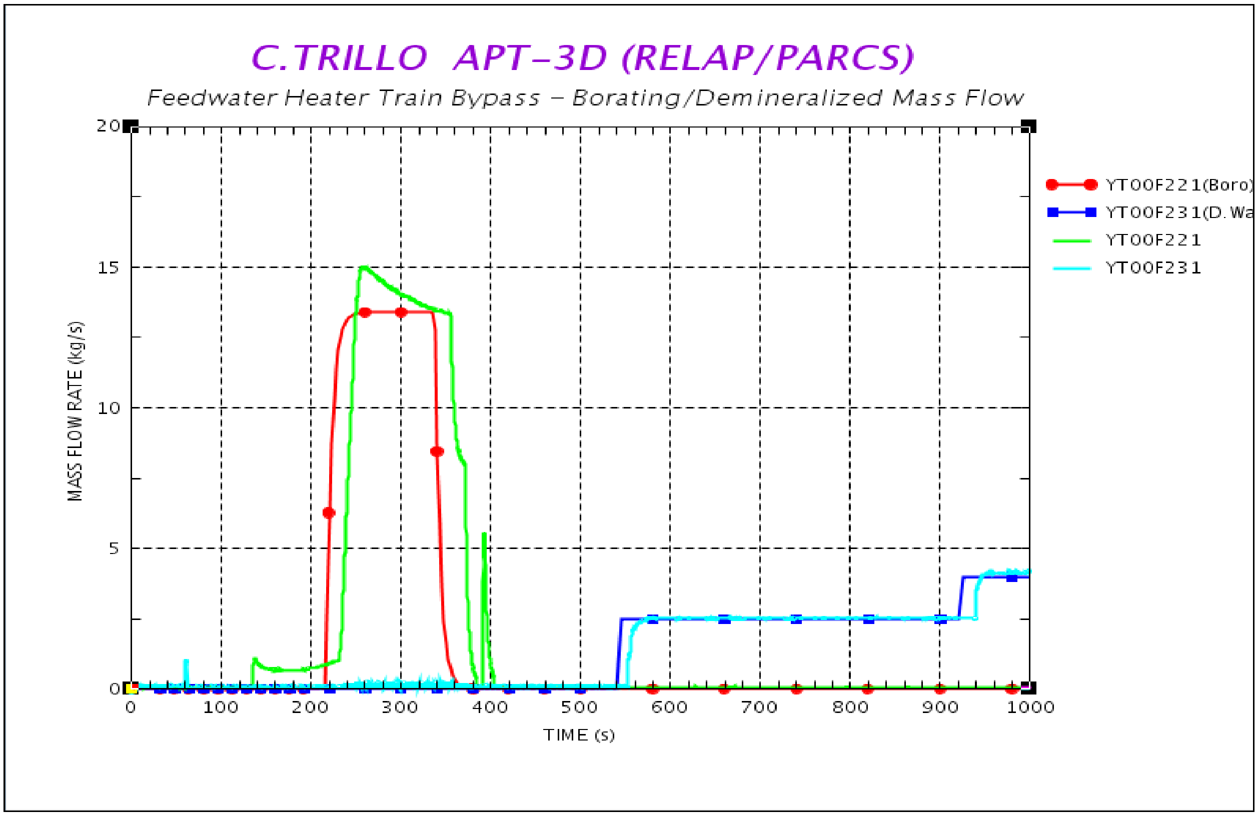

Fig. 18. Boron and Demineralised water injection.

All the plant parameters compared in the previous figures are in good agreement with the correspondent plant records. The answer of the new 3-D core to the reactivity perturbations (moderator temperatures, fuel temperatures, control rods insertion depth, boron concentration), in terms of total power is almost perfect.

To reproduce the automatic movement of control rod banks in this particular scenario, it is necessary to match the real core behaviour that is analyzed in the following section.

6.2 Core Results

The plant evolution during this transient was actually driven by the axial power profile deformation that triggered the limits of PU-RELEB.

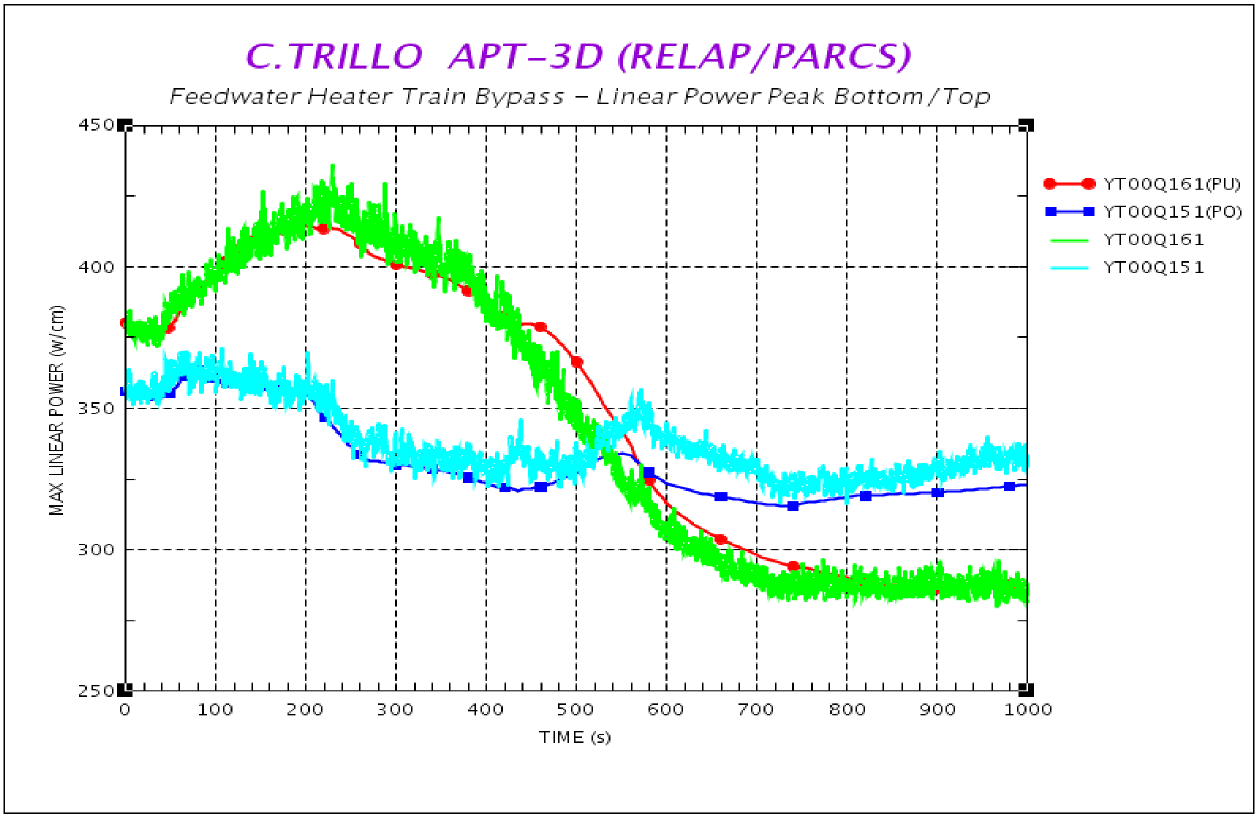

Fig. 19. In-core peaks. Bottom (PU) and top (PO).

The comparison of PO and PU signals calculated with the coupled model and the plant records indicate a very good approximation even after the stage at which rated power is impacted by the effect of boron injection and the turbine load reduction.

This is the key variable in this scenario and the driven force for develop the coupled methodology. The correct behavior of the calculated power density peak in the bottom section of the core, feeds the RELAP automatic simulation of PDDs, and finally triggers at the correct times the automatic countermeasures.

The PARCS calculated reactivity feedbacks due to the fuel, moderator, control rods and boron is included in the following figure.

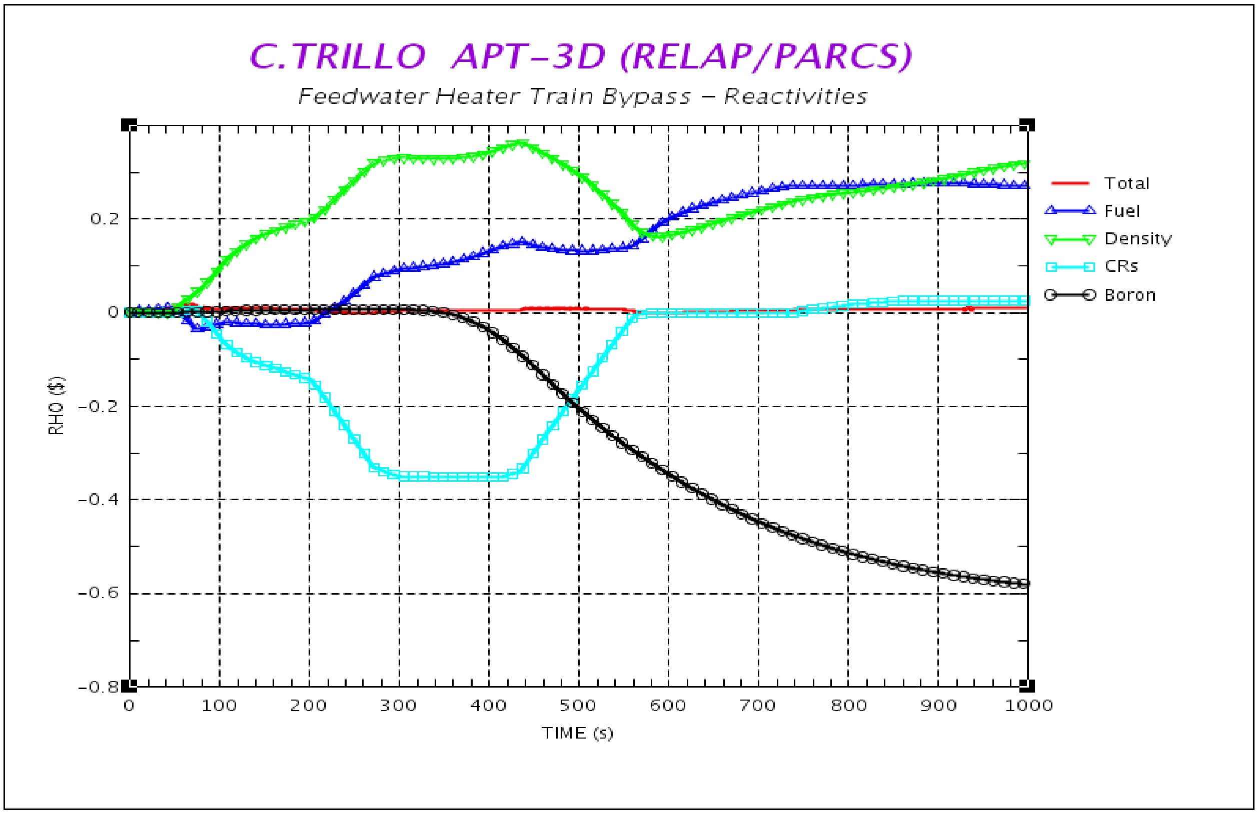

Fig. 20. Core Reactivities (PARCS).

The 3-D methodology for coupled core calculations allows the visualization of the full core conditions at the initial steady-state and during the transient.

The following 3-D figures helps to understand the in-core evolution of the main contributors to reactivity feedback, moderator temperature and fuel linear power or temperature.

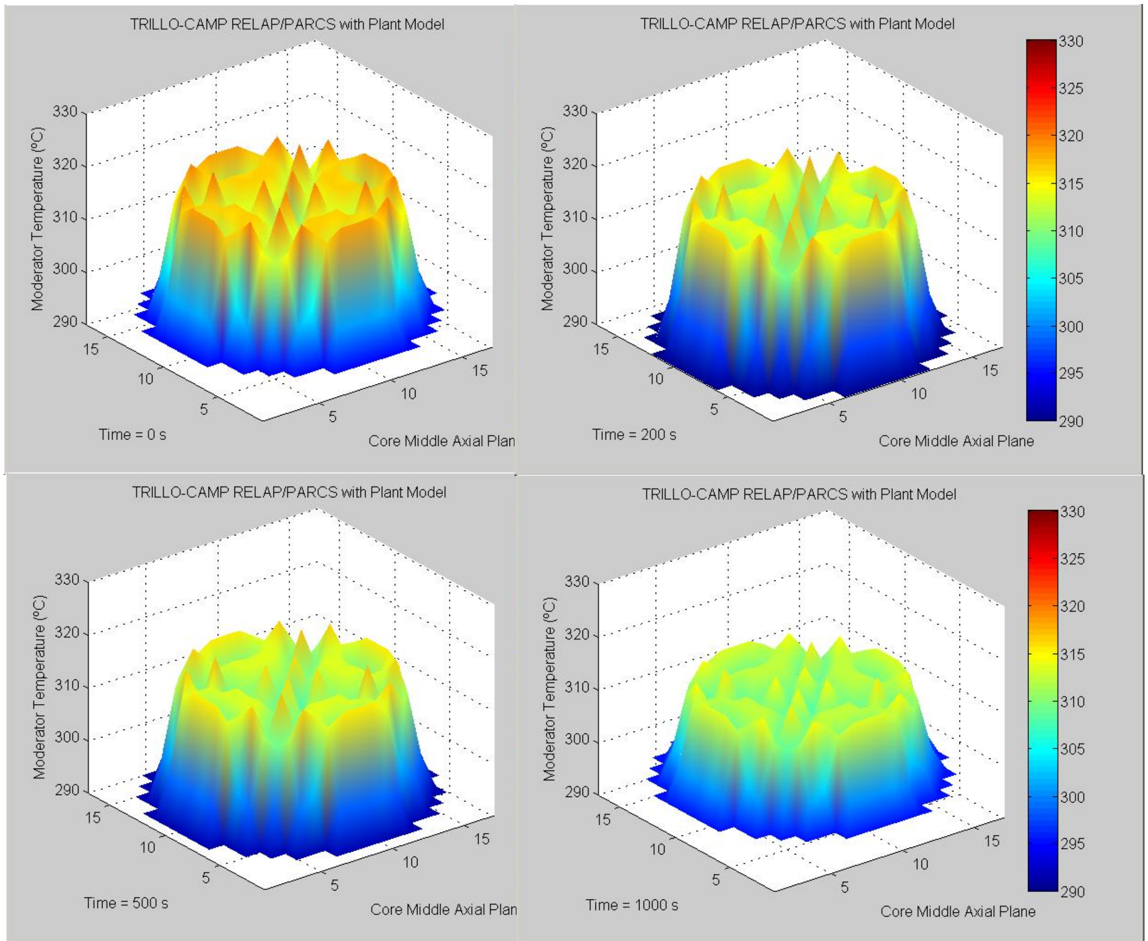

Fig. 21. Moderator Temperature Evolution. Core Middle Axial Plane.

In the sequence of figures to 0, 200, 500 and 1000 seconds, it is easy to follow a clear decrease in the moderator temperature at the beginning of the transient, by reducing the inlet temperature (without changing the radial core profile). In the subsequent power reduction the flattening of the radial core profile can also be identified.

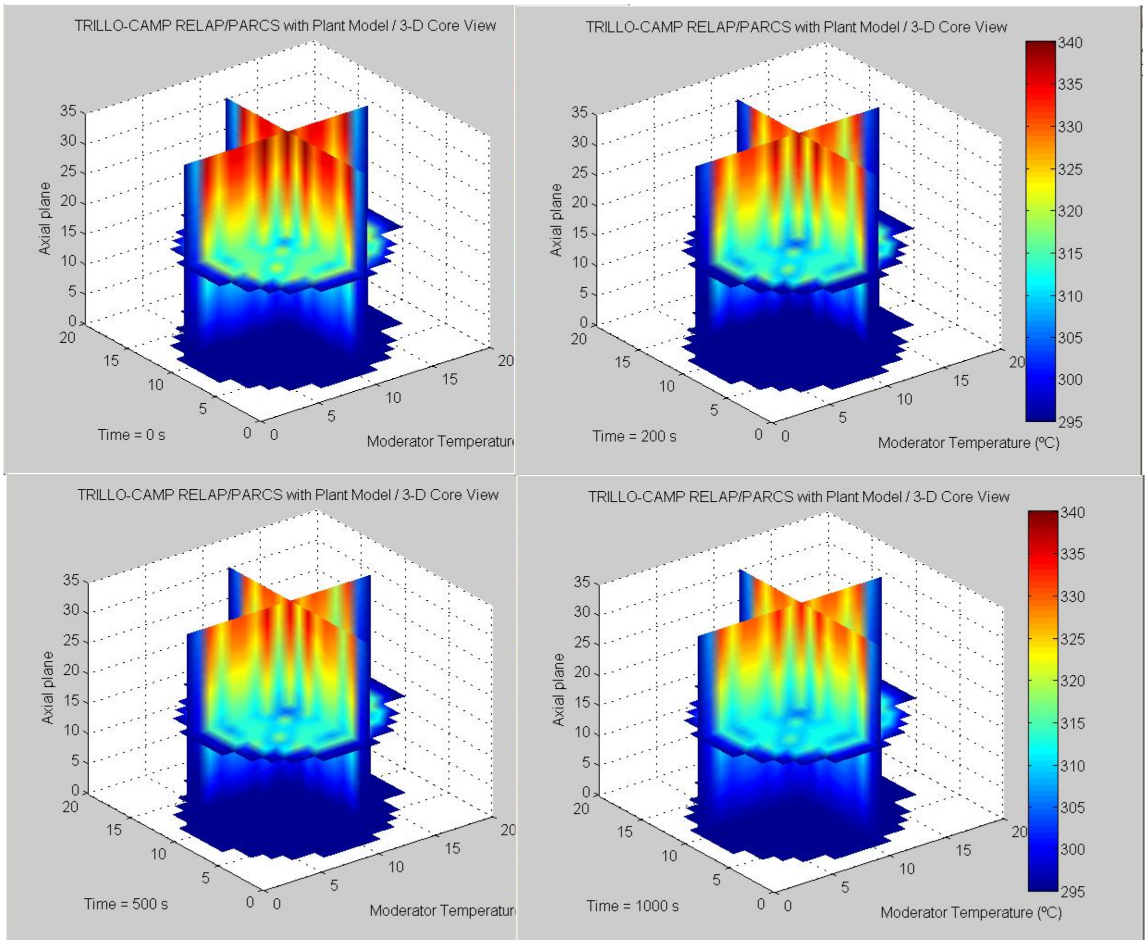

Fig. 22. Moderator Temperature Evolution. Core 3D Visualization.

In the core 3-D visualization, the moderator temperature distribution along the core and its variation along the transient can be analyzed. The temperature reduction focused in the lower part of the core at the beginning, and to the upper part after the power reduction.

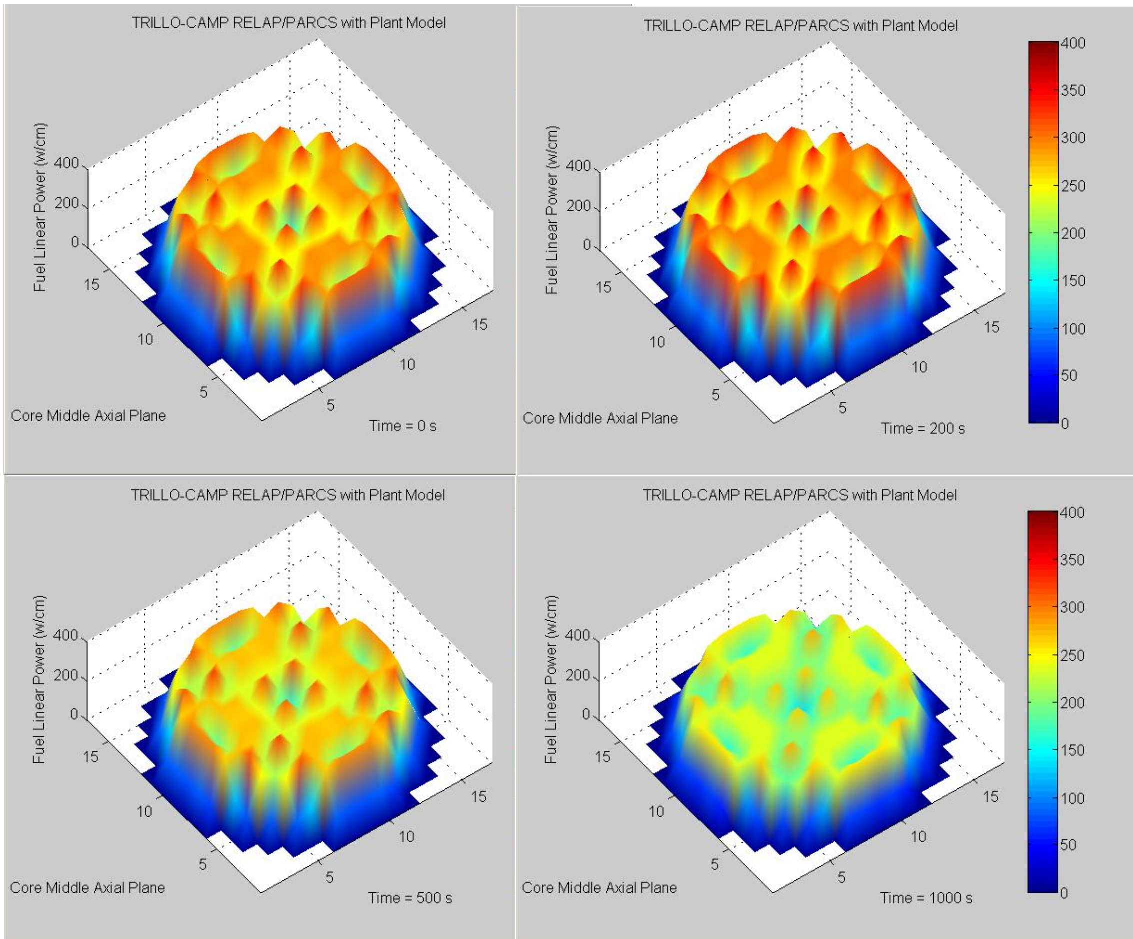

Fig. 23. Fuel Linear Power. Core Middle Axial Plane.

The linear power distribution in the fuel rods (middle axial plane of the core) reflects the initial power increase and the final power reduction.

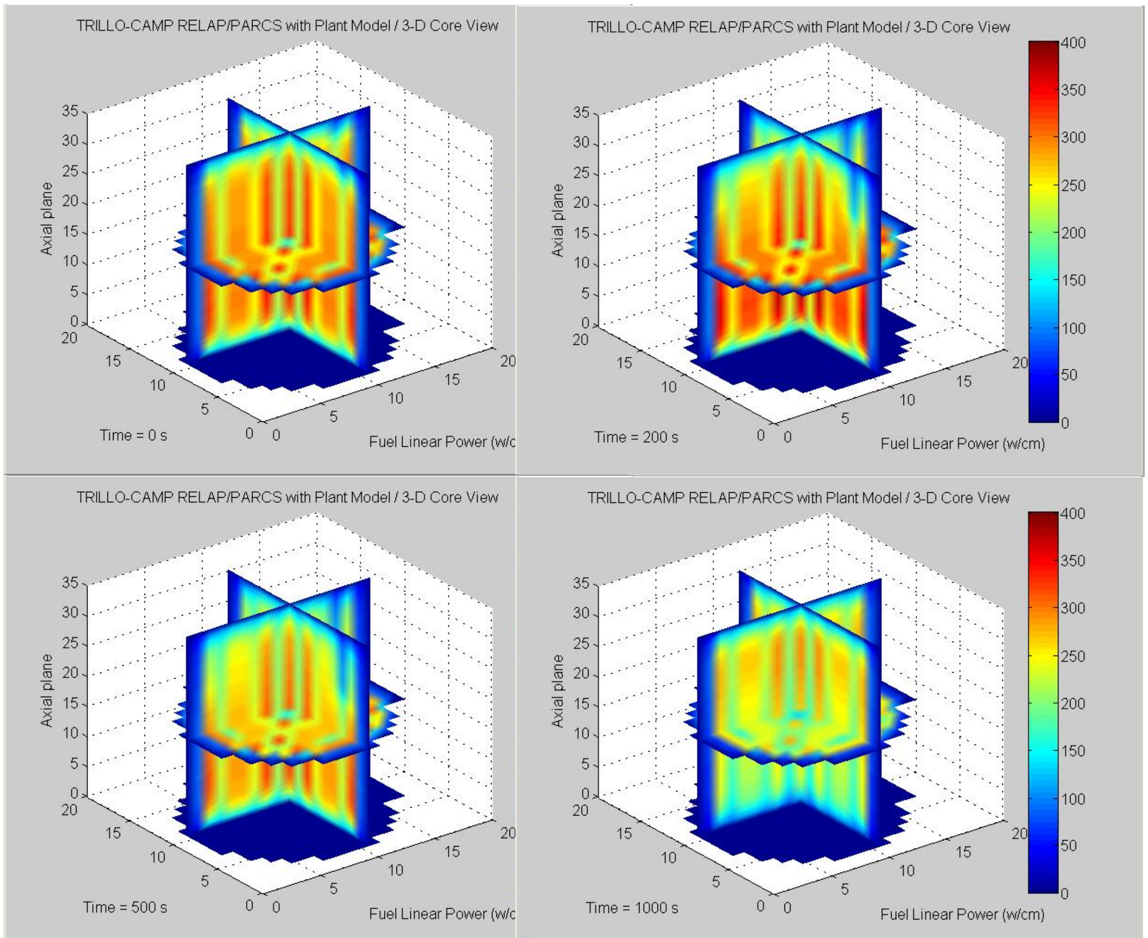

Fig. 24. Fuel Linear Power. Core 3D Visualization.

In the 3-D view of the linear power of fuel rods, it can be seen that the effect of initial power increase is more pronounced in the bottom core for the insertion of bank D. The subsequent progressive reduction of power, due to the bank's total insertion and boron injection, balances both parts of the core.

Finally, in the next figure is included a chart with the axial power profile evolution in the FA E-04 (HS-753), the one with PDD lance and maximum linear power.

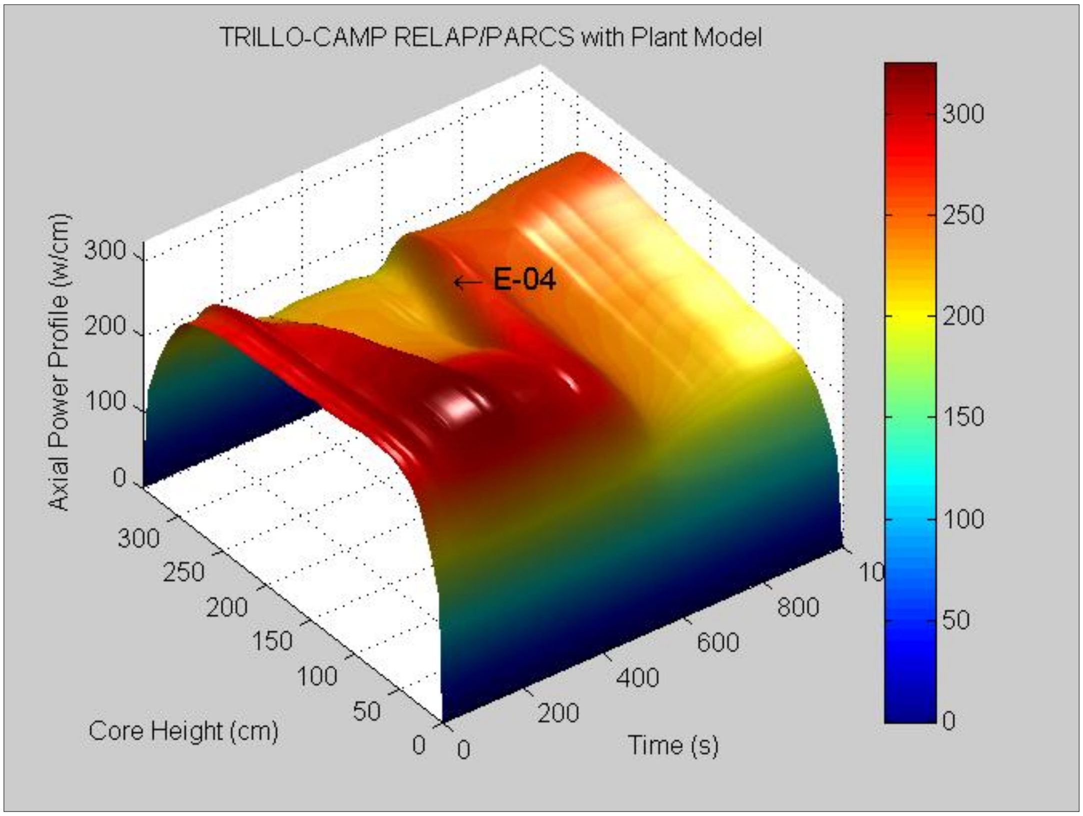

Fig. 25. Fuel Linear Power. Core 3D Visualization.

In this representation it can be perfectly seen the profile deformation toward the bottom of the core, which shows a maximum around 200 seconds, and is the responsible for the activation of the limits of PU.

The effect of borating pulse collaboration (t ~ 400 sec) is to depress the total linear power profile, while as D1 bank completes the insertion (t ~ 500 sec), the profile pivots from bottom skewed to top skewed.

The recovery of the inlet temperature by the turbine power reduction, accompanied by the cancellation of the effect of boron by injection of demineralised water, makes than the total power and the axial power profile reaches a stable situation at partial power.

7. EXECUTION STATISTICS

In this chapter the execution times of APT-0D and APT-3D are compared. The code versions are RELAP5/mod3.3_Patch1 and PARCS v2.7. The computer used is a “Intel(R) Core(TM)2 Duo CPU P8700 @ 2.53GHz”.

The first comparison is between steady-state calculations, both of them realized only with RELAP5/mod3.3 but different nodalization. The core model expansion increased the size of APT model from:

- Hydraulic Volumes 656 -> 2106 (3 times)
- Heat Structures 204 -> 1654 (8 times)

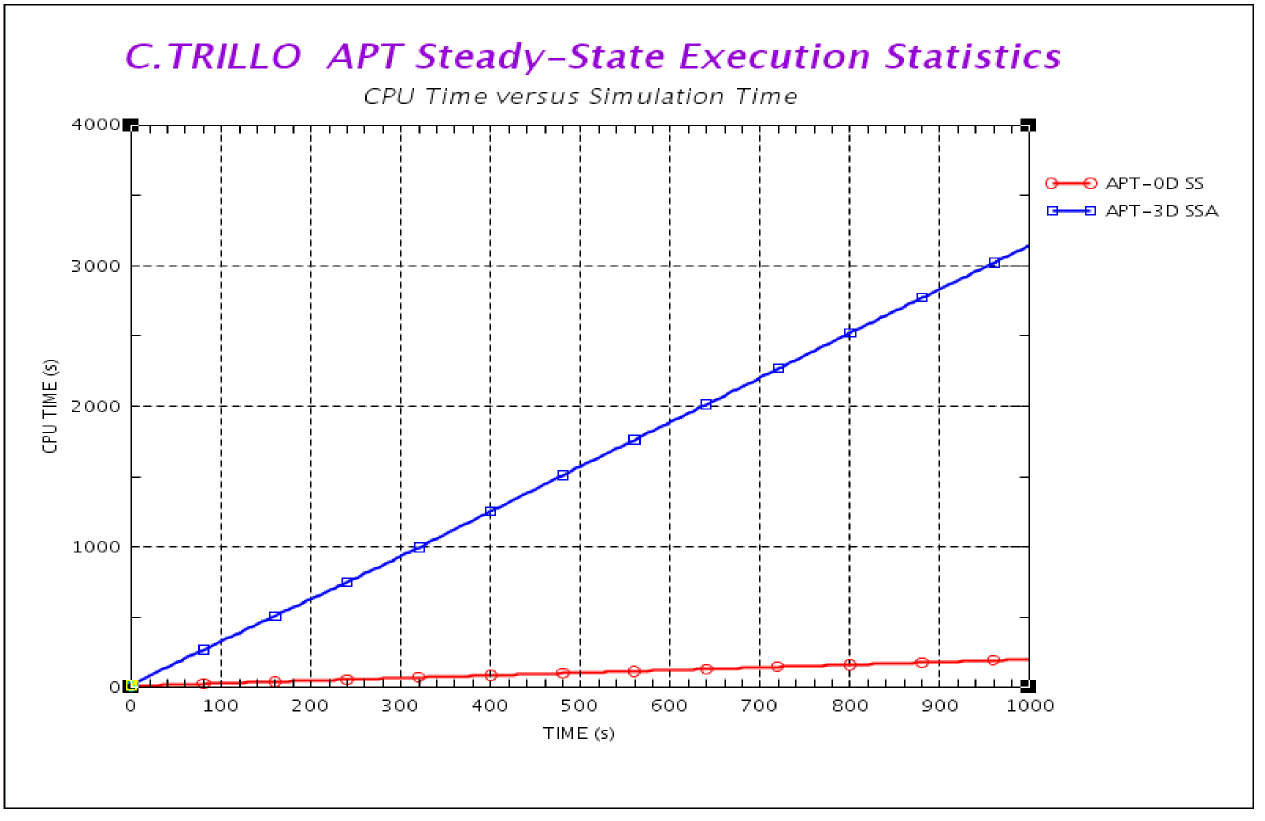

Fig. 26. RELAP Steady-State Execution Statistics.

The CPU time for the initialization of the plant model (1000 sec simulation time) increased from 199 sec in APT-0D (5 times faster than real time) to 3145 sec in APT-3D (3 times slower than real time).

The factor between both RELAP5 models APT-3D / APT-0D was around 16.

The second comparison is between transient calculations, the APT-0D was performed only with RELAP5/mod3.3, and the APT-3D with the coupled RELAP/PARCS. So the differences between both calculations include the model expansion and kinetic model:

- Hydraulic Volumes 656 -> 2106 (3 times)
- Heat Structures 204 -> 1654 (8 times)
- Point kinetic (RELAP) -> 3D kinetic (PARCS)

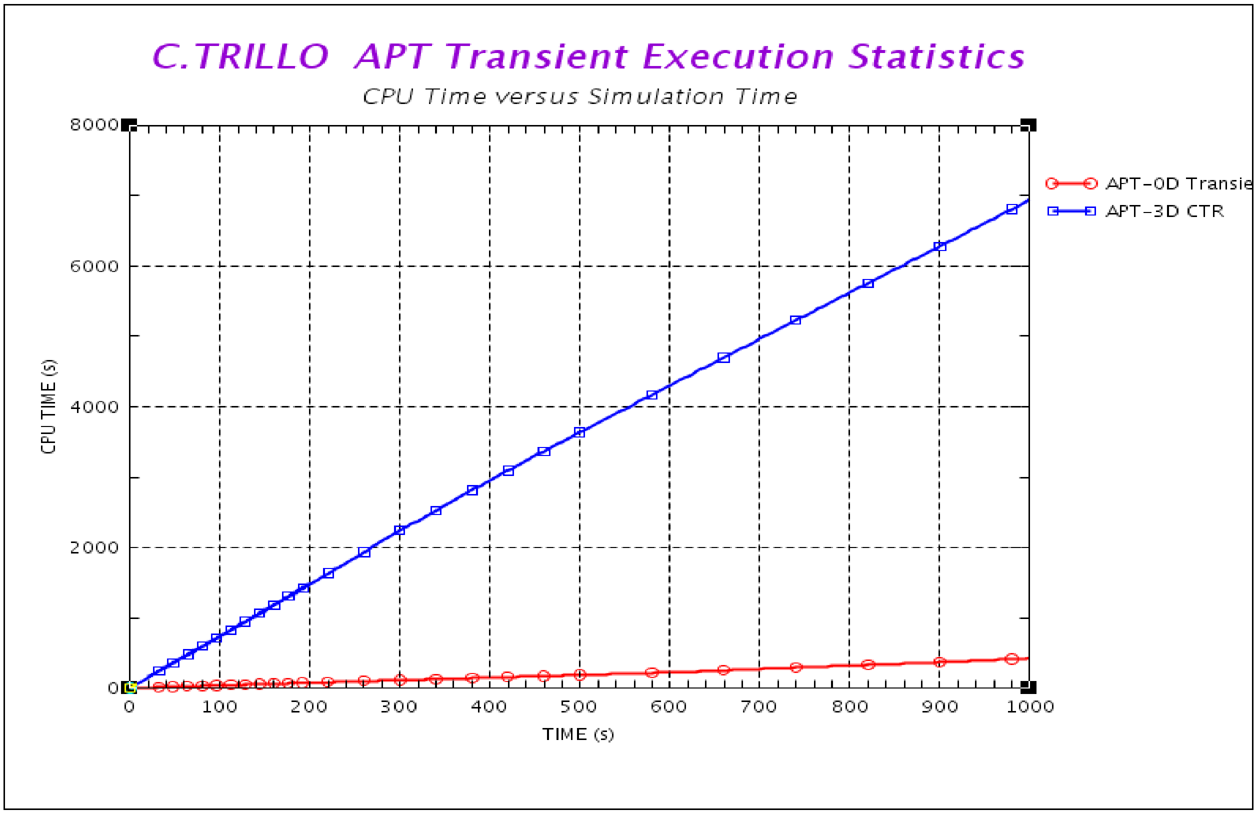

Fig. 27. RELAP Transient Execution Statistics.

The RELAP CPU time for the transient (1000 sec simulation time) increased from 424 sec in APT-0D (2.3 times faster than real time) to 6940 sec in APT-3D (7 times slower than real time).

The factor between RELAP5 executions APT-3D / APT-0D was maintained around 16.

The PARCS CPU time for the transient, not included in (Fig. 27), was 12,283 sec. (12 times slower than real time).

Table 2. Execution Statistics

	APT-0D	APT-3D		
	RELAP	**RELAP**	**PARCS**	**Total**
Steady-State	199	3,145		
Transient	424	6,940	12,283	19,223

So the total CPU time was 19,223 sec. 68% employed by PARCS and 32% by RELAP5. The factor between the RELAP/PARCS transient APT-3D / RELAP APT-0D was around 45.

The conclusion is that the important increase in the execution time of the transient when moving from APT-0D to APT-3D is due mostly to PARCS execution time and partially to the increase in the size of RELAP5 model.

8. CONCLUSIONS

The coupled RELAP/PARCS methodology for full plant applications has been developed and used for the first time with Trillo Plant Analyzer APT-3D.

This first novel application has been a real challenge to the coupled simulation capacities, as included inherent reactivity perturbations and also rod control movements and changes in boron concentration.

The precise reproduction of the core axial profile evolution during the transient was a crucial input to the in-core and ex-core systems simulations that conduct the automatic plant dynamic behavior.

The important increase in the execution time of the transient when moving from APT-0D to APT-3D is due mostly to PARCS execution time and partially to the increase in the size of RELAP5 model.

The results obtained validate the coupling methodology extended to full plant models, and the proper settings of the codes modifications related to control rod movement and boron concentration.

9. REFERENCES

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