

EXTERNAL COUPLING OF MODERN AND LEGACY MULTI- PHYSICS CODES WITH APPLICATION TO PBMR

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EXECUTIVE SUMMARY

The Pebble Bed Modular Reactor (PBMR) is a power plant that utilizes a High Temperature Reactor (HTR) and a closed-cycle gas turbine power conversion system. Many man-years of compiling a safety analysis report are involved in obtaining a licence from a national nuclear regulatory authority. Multiple computer code systems must be integrated to perform the required calculations.

In PBMR (Pty) Ltd, this integration is currently performed offline, without the ability to capture time-dependent circular feedback effects. The main codes used for transient calculations involving the reactor are the 2D neutronics code TINTE and the thermal-fluids systems code Flownex Nuclear. A time history trace of thermal-fluid boundary conditions is first calculated by Flownex Nuclear and then used by TINTE.

The purpose of this research was to establish an integrated time-dependent design and safety analysis capability, with the ability to perform detailed simulation and control of all reactor plant modes and transitions.

The Nuclear Engineering Analysis (NEA) Simulator, which is based on existing simulator architecture, was established to integrate and coordinate these types of analyses. The NEA Simulator enabled progressive development of the integrated simulation, with a fundamental understanding of external coupling of these codes.

TINTE-calculated reactor outlet temperature and total power are used to influence time-dependent system flow behaviour. Variable simulation time steps are introduced to accelerate integrated simulations. Continuous local time-step management for the TINTE temperature solver is implemented in the TINTE–NEA Simulator interface to make it resilient.

Explicit external coupling of two open-loop thermal-fluid models with circular dependencies produced acceptable results for fixed pressure transients, but not when pressure was solved. The parallel coupling was the most stable and versatile coupling analysed in this research; it also works for transients where pressure is solved. Important building blocks were established to simulate plant modes and transitions continuously.

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How can one measure or put a value on moral and emotional encouragement to complete a complex task such as this thesis? I personally do not think it is possible or even desirable, and am therefore content to express thanks.

First of all to my Creator, through whom all things are possible. Certainly very close after that, to my support structure at home, which played such a vital role – my lovely wife Ezna and our two (very young) beautiful daughters, Reinette and Anri.

PBMR (Pty) Ltd afforded me the opportunity to start, carry out and complete this work. Numerous people were involved in answering my questions, patiently playing the role of a sounding board, actively giving guidance, reviewing and editing. These people are Dr Onno Ubbink (supervisor), Frederik Reitsma (colleague), Gert van Heerden (colleague), Gerhard Strydom (colleague), Dr Jenny Huang (colleague), Dr Johan Strauss (colleague), Dr Hans Gougar (colleague), Jeetesh Keshaw (colleague), Ivor Clifford (colleague) and Denise Ansell (colleague).

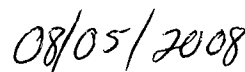
Thank you!

DECLARATION

I, the undersigned, hereby declare that the work contained in this project is my own original work.



Johannes Abraham Odendaal



Date

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ABBREVIATIONS

This list contains the abbreviations used in this document.

Abbreviation or Acronym	Definition
0D	zero-dimensional
1D	one-dimensional
2D	two-dimensional
3D	three-dimensional
API	Application Programming Interface
CBCS	Core Barrel Conditioning System
CCS	Core Conditioning System
CFD	Computational Fluid Dynamics
COBRA-TF	Coolant Boiling in Rod Arrays Code (Two-Fluid)
CORBA	Common Object Request Broker Architecture
FRAPTRAN	Fuel Rod Analysis Program Transient
GENFLO	GENeral FLOW
GUI	Graphical User Interface
HEXTRAN	Finnish advanced 3D reactor nodal dynamic code
HICS	Helium Inventory Control System
HTR	High Temperature Reactor
MPS	Main Power System
NEA	Nuclear Engineering Analysis group at PBMR (Pty) Ltd
NEM	Nodal Expansion Method
ORB	Object Request Broker
PBMR	Pebble Bed Modular Reactor
PBMR (Pty) Ltd	Pebble Bed Modular Reactor (Proprietary) Limited
PC	Personal Computer
PCU	Power Conversion Unit
PVM	Parallel Virtual Machine
ROMO	Linear Rod Motion Model
ROT	Reactor Outlet Temperature
SAS	Small Absorber Spheres
SCADA	Supervisory Control and Data Acquisition
SMABRE	SMAll BREak
SSC	Structures, Systems and Components

Abbreviation or Acronym	Definition
TINTE	Time Dependent Neutronics and Temperatures
TRAC	Transient Reactor Analysis Code
TRAC-BF1	TRAC for Boiling Flow
TRAC-PF1	TRAC for Pressurized Flow
USA	United States of America
VTT	Technical Research Centre of Finland
VVER	Vodo-Vodyanoi Energetichesky Reactor

NOMENCLATURE

This list contains the nomenclature used in this document.

Abbreviation or Acronym	Definition
Comp	Component
ConX	Normalized control rod position
ζ	Damping coefficient
f	Frequency in Hz
HP	High pressure HICS mass flow
K	Gain
LP	Low pressure HICS mass flow
$\dot{m}$	Mass flow
N?	Node
P	Pressure
RodP	Control rod position
s	Laplace operator
T	Sampling time
T	Temperature
ω_n	Natural or cut-off frequency in rad/s
z	Discrete time operator for the z -transform

DEFINITIONS

This list contains the definitions used in this document.

Term	Definition
CORBA	Common Object Request Broker Architecture. A networked, cross-platform protocol allowing for the exchange of data between computer nodes.
Evaluation Model	Calculational framework for evaluating the behaviour of the reactor system during a postulated accident event, which includes one or more computer programs and all other information needed for use in the target application [1].
Explicit Coupling	A fully explicit coupling is when the only new time parameters that appear in the discretized equations are in the representation of the temporal derivative.
External Coupling	The external coupling method gives preference to the neutronics, thermal fluids and heat transfer calculations of the core to be performed with the neutron kinetics code. A thermal fluid system code is then used for the thermal fluids calculations of the rest of the reactor circuit.
Fixed Pressure Transient	During a fixed pressure transient the pressure at one node of the flow network is fixed and used as a (time dependent) boundary condition. The pressure in the rest of the flow network as well as the mass flow for the total flow network will then be calculated as a result of this. The fluid inventory will be a result of the system pressures.
Implicit Coupling	A fully implicit coupling is when the only old time parameters that appear in the discretized equations are in the representation of the temporal derivative and result in simultaneous spatial coupling of all independent variables.
Indirect Coupling	Indirect Coupling involves the replacement of the detailed reactor thermal fluids and heat transfer model of the thermal fluid system code with a pipe element that has similar pressure drop and reactor outlet temperature. Thermal fluid conditions at the reactor inlet and outlet are transferred to the neutron kinetics code, but the reactor pressure drop and outlet temperature of the neutron kinetics code are used to update the pipe element in the thermal fluid system code.
Internal Coupling	Internal coupling leaves the thermal fluid system code to perform all thermal fluids and heat transfer calculations for the entire reactor circuit, including the core. A neutron kinetics code will then only calculate reactor kinetics with the relevant core data being transferred between the codes node by node.
Model	A simplified version of something complex such as a mathematical model used, for example, to analyse and solve problems or make predictions.
Model Set	A group of models combined to perform a task.
Node	A Personal Computer (PC) participating in the simulation.

Term	Definition
Parallel Coupling	Parallel coupling leaves the core thermal fluids and heat transfer to be calculated by both the neutron kinetics and thermal fluid system codes. In this case, the thermal fluid conditions at the reactor inlet and outlet are transferred to the neutron kinetics code, while power distributions are transferred node by node to the thermal fluids system code.
SCADA	Supervisory Control and Data Acquisition. A category of software application programs for process control. SCADA systems are typically used to perform data collection and control at the supervisory level, as the system itself is not critical to control the process in real time.
Scenario	A target operation with a sequence of possible events.
Schedule	A plan of work to be done in a specified order and at specified times.
Simulation	The construction of a mathematical model to reproduce the characteristics of a phenomenon, system or process, often using a computer, in order to solve a problem.
Simulator	A device, instrument, or piece of code designed to reproduce essential characteristics or features of a phenomenon, system or process, for example, a power plant simulator.
Solved Pressure Transient	During a solved pressure transient pressure and mass flow are calculated for the total flow network. The fluid inventory will be a result of all mass flow into and out of the system.
Tag	A label that classifies a piece of data, for example, the electrical power output of a power turbine.
Thermal Fluids	Thermal fluids have to do with the simultaneous solution of coupled flow, pressure and temperature distribution of either gas, liquid or gas-liquid mixtures in thermal fluid networks. Traditionally in the light water reactor nuclear industry, the more specific term ‘thermal-hydraulics’ has been used, and is still in use today, due to the fact that the primary fluid is a liquid. In this thesis, the term ‘thermal fluids’ has been used to include both, except where specific reference to the latter is quoted in the text.

1. INTRODUCTION

1.1 BACKGROUND

The Pebble Bed Modular Reactor (PBMR) is a power plant that utilizes a High Temperature Reactor (HTR) together with a closed-cycle gas turbine power conversion system. Pebble Bed Modular Reactor (Proprietary) Limited (PBMR (Pty) Ltd) of South Africa, established in 1999, is developing the PBMR, and is internationally regarded as one of the role players in nuclear energy. Their focus is to develop and market small-scale HTRs for the local and international markets. The PBMR is not the only HTR currently being developed in the world, but is the only HTR that utilizes pebble fuel in the reactor coupled to a direct closed-cycle gas turbine power conversion system. The reactor layout enables high levels of passive safety, as expected of advanced nuclear designs, and the direct cycle makes high efficiency and attractive economics viable. [2]

In the world of nuclear plant design and licensing, many computer code systems are used to calculate the diverse technical aspects of the entire plant. As the nuclear industry is one of the most regulated industries in the world today, calculations focused on detailed behaviour of plant Structures, Systems and Components (SSC) are as important as calculations involving the entire plant. To obtain a licence from a national nuclear regulatory authority generally involves many man-years of compiling and presenting a safety analysis report that covers all aspects of the nuclear plant construction, commissioning, operation and decommissioning. The backbone of this report is a multitude of calculations that in most cases are relevant to nuclear safety.

To be able to perform calculations for nominal and accident conditions that involve the entire plant, multiple computer code systems, and in some cases hand calculations, need to be integrated into what is known as an Evaluation Model¹. This is necessitated by the many diverse sub-calculations required to present the overall calculation. In general [1], a systems code is required as part of the Evaluation Model that describes the transport of fluid mass, momentum and energy throughout the reactor coolant systems.

Currently in PBMR (Pty) Ltd, Evaluation Model sub-component integration is performed in an offline manner. Analysts complete individual calculations in isolation with boundary conditions on the interface between components provided by other components. This process is also generally referred to as the 'calculational train'. An obvious deficiency in this method is the ability to capture time-dependent feedback effects that result in circular

¹ Refer to the definition of Evaluation Model.

dependencies between components. Steady-state and time-dependent integration of these calculations falls into the field of multi-physics.

Multi-physics deals with simulations that involve multiple physical models or multiple simultaneous physical phenomena. For example, combining chemical kinetics and fluid mechanics or combining neutronics with thermal fluids. Multi-physics typically involves solving coupled systems of partial differential equations that have time-dependent cross-terms. In many cases, to get accurate results, it is important to include mutual dependencies where the material properties significant for one field (such as the neutron absorption cross section) vary with the value of another field (such as temperature), and vice versa. ([3], [4])

Due to the long history of the world nuclear industry, many computer code systems have been developed over the years, mainly in old FORTRAN. Many of these computer codes are still in use today, and are generally referred to as 'legacy codes'. More modern computer codes are also in use today, developed using the latest technology and according to the latest quality requirements imposed by the national nuclear regulatory authorities. This is also true for PBMR (Pty) Ltd.

1.2 CURRENT STATUS

Currently in PBMR (Pty) Ltd, transient design and accident analysis calculations involving the reactor and Power Conversion Unit (PCU) are performed with Time Dependent Neutronics and Temperatures (TINTE) [5] and Flownex Nuclear [6] coupled to Simulink [7].

TINTE is a nuclear safety-relevant analysis code that is used to calculate time-dependent neutronics. It models the pebble bed reactor core under transient conditions and provides a two-dimensional (2D) coupled solution for the two energy group kinetics, thermal fluids, heat transfer and corrosion (graphite–air interaction). TINTE is a legacy code and was developed over a period of 20 years, mostly in FORTRAN 77, with some sections in FORTRAN 90. [5]

Flownex Nuclear is a modern one-dimensional (1D) thermal-fluids systems code, also referred to as a systems Computational Fluid Dynamics (CFD) code due to its ability to link components of varying levels of complexity (lumped, 1D, 2D or 3D CFD) together in a thermal-fluid network. It can be used for both steady-state and transient analysis of large and complex unstructured thermal-fluid networks, and guarantees preservation of mass, energy and momentum. Flownex Nuclear also includes a multidimensional networked nuclear reactor model to account for the thermal-flow behaviour of the reactor core and core structures. The coupled time-dependent neutronics calculations of the reactor are performed with a zero-dimensional (0D) model, also known as a point kinetics model. [6]

Simulink is a general-purpose diagrammatic modelling environment with the ability to model any combination of mixed and/or discrete components of differential equations. In PBMR (Pty) Ltd, it is mainly used for the design of control algorithms.

TINTE and Flownex Nuclear are linked in an offline manner. A history trace of thermal-fluid boundary conditions for the reactor is first calculated by Flownex Nuclear and then used by TINTE for the same transient calculation. In this way, no feedback or mutual dependency effects between TINTE and Flownex Nuclear are taken into account. To enable accurate system responses in the PCU, Simulink is coupled to Flownex Nuclear in a time-dependent manner and used to control valves and actuators during the transient. Thus Simulink models the operational control system.

Previous work related to the external coupling of Flownex Nuclear to two different time-dependent neutronics (reactor kinetics) codes is described in [8] and [9]. Similar coupling schemes were used, which produced usable results. One of these codes was TINTE [8].

1.3 MULTI-PHYSICS PROBLEM

PBMR (Pty) Ltd needs an integrated time-dependent design and safety analysis capability utilizing the TINTE, Flownex Nuclear and Simulink codes due to the following:

- TINTE is the official pebble bed reactor transient analysis code used for nuclear safety-relevant calculations involving neutronics and heat transfer in the core.
- Flownex Nuclear is the official thermal-fluids systems code used for nuclear safety relevant calculations of the total system.
- Simulink is used to design and run the plant control algorithms when integrated with Flownex Nuclear.
- Multiple Flownex Nuclear models are utilized to model all the important thermal-fluid phenomena of the entire plant due to the size and complexity of models required. However, these models have time-dependent circular dependencies and need potential external integration.
- Detailed simulation and control of all plant modes of operation involving the reactor and transitions between the modes have not been done.

Seamless coupling of these time-dependent multi-physics models is therefore of the utmost importance, and the topic of this thesis. To assist in the validation and verification of code components, it will be beneficial if all the individual model calculations can be redone afterwards in an isolated and independent manner. It should be possible to use the inputs generated by the integrated simulation to obtain the same individual results.

1.4 AIM OF RESEARCH

The aim of this research is twofold:

- To gain a fundamental understanding of external coupling of time-dependent multi-physics code systems.
- To establish a platform to integrate and coordinate these types of analyses.

The basis for this platform will be a shelved Common Object Request Broker Architecture (CORBA) based simulator [10]. As the author was involved in the development of the simulator, it was a natural choice to try and leverage on the original investment made by PBMR (Pty) Ltd.

The type of project is mainly design with an emphasis on development and simulation. The method of investigation will focus on analysis of available literature sources, and a progressive investigation into the coupling of TINTE to Flownex Nuclear and Simulink.

The progressive investigation will be as follows:

- Adapt the existing CORBA-based simulator architecture, supplied by PBMR (Pty) Ltd, to focus on integrating time-dependent design and analysis code systems.
- Develop the time-dependent TINTE link and integrate it into the simulator architecture.
- Verify that the simulator link to Flownex Nuclear is still current, and update if necessary.
- Use the updated simulator architecture to investigate the differences between closed-loop and externally linked simulation scenarios. This will be done by using an existing closed-loop Flownex Nuclear thermal-fluid Main Power System (MPS) model, and modifying it as appropriate.
- Configure an MPS simulation scenario with the TINTE reactor and Flownex Nuclear PCU models in a direct coupling. Investigate the viability and limitations of this approach.
- Configure an MPS simulation scenario with the TINTE reactor, Flownex Nuclear reactor and Flownex Nuclear PCU models in a hybrid direct and indirect coupling with a Simulink model to facilitate transient control. In this scenario, the Flownex Nuclear reactor model will only calculate thermal fluids; its neutronics input will be calculated by TINTE. Investigate the viability and limitations of this approach.

The impact of the above multi-physics code coupling for PBMR (Pty) Ltd will be:

- The time-dependent TINTE link can be used as a benchmark for other reactor transient analysis simulations.

- The time-dependent TINTE link can be used in large integrated design and analysis simulation scenarios, containing multiple Flownex Nuclear and Simulink models. This integrated set-up can be used to:
 - Design and test the required operational controller algorithms.
 - Verify the initial start-up and commissioning philosophy.
 - Verify most of the neutronics and thermal-fluid functional behaviour regarding operational modes and states for normal operation.
 - Validate the functional time-dependent neutronics and thermal-fluid characteristics of the integrated reactor model in the Training Simulator.

1.5 LAYOUT OF THESIS

Chapter 2 provides a survey of work that was done prior to, or is related to, this research. Different coupling methodologies are investigated, and an overview of some coupled code systems is provided. An overview is also presented of the existing CORBA-based simulator architecture, and an explanation is given of how it should be possible to implement the different coupling methodologies. This chapter forms the foundation for the rest of the research that will be conducted.

The Software Architecture employed, modified and developed during this research is explained in detail in Chapter 3. It starts with the modified CORBA-based simulator architecture, now called the Nuclear Engineering Analysis (NEA) Simulator, and continuous with simulation time-step management. A critical aspect of the NEA Simulator is its ability to communicate to the hosting software applications on an Application Programming Interface (API) level. This is discussed in great length, especially the new interface that needed to be developed to TINTE. The last feature of the software architecture to be discussed is the ability to integrate custom-built, time-dependent applications into the simulation scenario.

This leads to the Integrated Simulation, which is discussed in Chapter 4. A progressive investigation of different coupling configurations and methodologies is presented. It starts with an investigation into splitting a closed-loop Flownex Nuclear MPS model into a PCU and reactor model, and coupling the two halves externally. The newly developed TINTE interface is next, and coupling of TINTE to a Simulink model is discussed. After this, the external coupling of TINTE and the Flownex Nuclear PCU model is investigated. The chapter is concluded with the parallel coupling of TINTE with the Flownex Nuclear MPS model.

The proof is important, and Chapter 5 deals with test cases. Whereas Chapter 4 only presents some results to illustrate the integrated simulation issues, Chapter 5 presents

complete results for selected test cases. It starts with an application of the external Flownex Nuclear/Flownex Nuclear coupling, showing a fixed-pressure² load-follow transient. The external TINTE/Flownex Nuclear coupling follows, and a similar fixed-pressure transient is presented. Of the coupling methodologies investigated, the parallel TINTE/Flownex Nuclear coupling is by far the most versatile and stable. Solved pressure³ transients where are simulated; combined load follow, followed by control rod withdrawal and insertion. As an added bonus, results illustrating the application of variable simulation time steps are presented.

Finally, Chapter 6 presents the conclusions and recommendations for further work.

² Refer to the definition of Fixed Pressure Transient.

³ Refer to the definition of Solved Pressure Transient.

2. SURVEY OF PREVIOUS OR RELATED WORK

2.1 INTRODUCTION

Time-dependent coupling of multi-physics code systems is not new. The Technical Research Centre of Finland (VTT) started this process for their neutron kinetic and thermal-fluid system codes as long ago as the 1980s [11]. The overriding motivation for this has been the optimum use of existing codes and models where resources are limited. Insight into similar or related work done by others is very important for the efficient and effective use of limited resources, and an overview is given in this chapter. The overview is concluded in Section 2.4 with a brief discussion of the shelved CORBA-based simulator.

2.2 COUPLING METHODOLOGIES

In general, methods for coupling of thermal-fluid system and neutron kinetics codes can be divided into three groups: external (also referred to as direct [8]), internal and parallel. The external coupling method ([8], [11] and [12]) gives preference to the neutronics, thermal-fluids and heat transfer calculations of the core to be performed with the neutron kinetics code. A thermal-fluid system code is then used for the thermal-fluids calculations of the rest of the reactor circuit, with the interface data being the thermal-fluid conditions at the reactor inlet and outlet.

An important observation is that the external coupling method can be fully explicit, fully implicit or somewhere in-between. A fully explicit coupling is when 'the only new time parameters that appear in the discretized equations are in the representation of the temporal derivative'. The stability of explicit coupled systems is hampered by the sonic Courant limit; 'sonic phenomena (i.e. pressure wave propagation and resultant velocities) are not treated implicitly in the spatial terms'. A fully implicit coupling is when 'the only old time parameters that appear in the discretized equations are in the representation of the temporal derivative' and result in 'simultaneous spatial coupling of all independent variables' [13].

Internal coupling ([11] and [12]) leaves the thermal-fluid system code to perform all thermal-fluids and heat transfer calculations for the entire reactor circuit, including the core. A neutron kinetics code will then only calculate reactor kinetics with the relevant core data (temperatures and power distributions) being transferred between the codes node by node.

Parallel coupling ([11]) leaves the core thermal-fluids and heat transfer to be calculated by both the neutron kinetics and thermal-fluid system codes. In this case, the thermal-fluid conditions at the reactor inlet and outlet are transferred to the neutron kinetics code, while power distributions are transferred node by node to the thermal-fluids system code.

A slightly modified approach to the parallel coupling method ([8] and [9]) involves the replacement of the detailed reactor thermal-fluids and heat transfer model of the thermal-fluid system code with a pipe element that has similar pressure drop and reactor outlet temperature. Thermal-fluid conditions at the reactor inlet and outlet are transferred to the neutron kinetics code, but the reactor pressure drop and outlet temperature of the neutron kinetics code are used to update the pipe element in the thermal-fluid system code. This method is also referred to as indirect coupling [8].

2.3 OTHER CODE SYSTEMS

A short overview of the coupling of some other code systems is given in the following sections. In Section 3.3.1, more detail is given about the time step schemes employed by some of these codes.

2.3.1 WKIND/Flownex Nuclear [9]

WKIND [14] and Flownex Nuclear have been coupled with the indirect method (refer to Section 2.1) to demonstrate the advanced core modelling features that WKIND has to offer above the Flownex Nuclear reactor model. Both codes model the neutronics, heat transfer and thermal fluids of the 268 MW version of the PBMR reactor core, but Flownex Nuclear also models the PCU. This version of the PCU is still based on a previous configuration of the PBMR that incorporates a three-shaft Brayton cycle instead of the current single-shaft Brayton cycle design. WKIND offers a reactor core simulation, based on multidimensional neutronics and thermal fluids, which models realistic fuel temperatures during fast transients. Representative transient cases have been calculated by both code systems to demonstrate that the indirect coupling with external models works sufficiently. A hypothetical fast insertion of reactivity was simulated to demonstrate the advanced features of WKIND.

2.3.2 TINTE/Flownex Nuclear [8]

The coupling of TINTE and Flownex Nuclear was based on the indirect method (refer to Section 2.1) with the aim of validating the point kinetics neutronics model incorporated in the Flownex Nuclear reactor model. This work followed after the WKIND/Flownex Nuclear coupling and was based on the same coupling technique. It also employed the three-shaft Brayton cycle and the 268 MW version of the PBMR reactor core.

TINTE has an active validation program for its transient neutronics and heat transfer calculation capabilities in the core. Due to this, the TINTE/Flownex Nuclear coupling has the advantage that it can be used to validate the Flownex Nuclear reactor model.

An interesting observation made in [8] is that the external explicit method for coupling was at first attempted, but did not work due to stability problems.

2.3.3 HEXTRAN/SMABRE [11]

The work in [11] focused on the validation of coupled codes developed in Finland for safety analyses of the light water reactors in design basis accidents. The HEXTRAN/SMABRE code system makes use of the parallel coupling method, and is intended to calculate Vodo-Vodyanoi Energetichesky Reactors (VVER) for hexagonal core lattices. These codes were developed separately. It became necessary to couple them, as the transients to be analysed have a strong coupling of neutronics, heat conduction and fluid dynamics.

SMABRE (=SMAll BREak) [15] implements five conservation equations for mass and energy for water and steam, and for the mixture of steam and water. It is similar to the typical system codes, can model the complete primary system of power plants, and also employs basic core neutronics in the form of point kinetics. SAMBRE uses a nodalization scheme to model 3D core thermal-fluid effects.

HEXTRAN [16] is a 3D reactor dynamics code that calculates neutronic, fuel heat transfer and thermal fluids within the reactor core. It employs the nodal expansion method and solves the two-group neutron diffusion equations. Four thermal-fluid conservation equations are solved: steam and water mass, total enthalpy and total momentum, and a selection of correlations.

The power distributions calculated by HEXTRAN are transferred to the system code SAMBRE node by node, with the thermal-fluid data only transferred at the core inlet and outlet. Both codes calculate the thermal fluids of the core. Usually, a detailed nodalization of the core is used for HEXTRAN and a coarse nodalization of the core for SMABRE.

2.3.4 FRAPTRAN/GENFLO [11]

As was mentioned previously, the work in [11] focused on the validation of coupled codes developed in Finland for safety analyses of light water reactors in design basis accidents. The FRAPTRAN/GENFLO code system makes use of the parallel coupling method. GENeral FLOW (GENFLO) [17] is used for sub-channel calculations around a single fuel rod and outputs the heat transfer on the cladding surface. Fuel Rod Analysis Program Transient (FRAPTRAN) [18] uses the heat transfer on the cladding surface as the boundary condition, and calculates deformation of fuel pellets and cladding and fuel rod temperatures, including potential ballooning.

In a large break loss-of-coolant-accident, the stand-alone FRAPTRAN calculations suggested ballooning, cladding deformation and rod failure due to the partly unrealistic boundary conditions. With the FRAPTRAN/GENFLO coupling, no cladding ballooning was predicted.

2.3.5 TRAC-PF1/NEM/COBRA-TF and TRAC-BF1/NEM/COBRA-TF [12]

The Pennsylvania State University has performed the coupling of the Transient Reactor Analysis Code for Boiling Flow (TRAC-BF1) [19] and Transient Reactor Analysis Code for Pressurized Flow (TRAC-PF1) [20] codes with 3D Nodal Expansion Method (NEM) neutronics [21]. TRAC-BF1 and TRAC-PF1 calculate 3D thermal-fluid conditions in the core. Afterwards, they proceed with the coupling of Coolant Boiling in Rod Arrays Code (Two-Fluid) (COBRA-TF) [22] to TRAC-PF1/NEM and TRAC-BF1/NEM respectively. COBRA-TF is an advanced thermal-fluid sub-channel code that can calculate detailed heat fluxes and temperature profiles in the fuel pins, as well as departure from nucleate boiling ratio around the fuel pins.

The TRAC-PF1/NEM and TRAC-BF1/NEM couplings are based on the internal coupling method, whereas COBRA-TF is externally coupled to these two codes, and receives power and thermal-fluid boundary values for its detailed sub-channel calculations.

The software architecture employed for the coupling is Parallel Virtual Machine (PVM); it makes the coupled code system very flexible. Multiple computing nodes can be used simultaneously and some of the individual codes can even be split up using this technology.

Because the internal coupling method is used, 'development of appropriate nodalization and mapping schemes between thermal-hydraulics core model, heat-structure/rod model, and neutronics model is very important and needs to be done in both the axial direction and the radial plane'.

2.4 EXISTING CORBA-BASED SIMULATOR

The existing CORBA-based simulator [10] architecture was developed at PBMR (Pty) Ltd between November 2001 and May 2004 for the purposes of a PBMR plant training simulator. At the end of this period, a strategic evaluation of the simulator showed that it was not fit for purpose as a training simulator, and it was shelved in favour of commercially based simulator architecture.

The basis for code integration when using the CORBA-based simulator architecture is that all models should run in parallel, i.e. data exchange will only occur at the end of the time step.

This was done to facilitate many time-dependent models running simultaneously in parallel. Coupling will therefore be external and explicit.

Some flexibility exists in the way that models are scheduled, in that multiple intervals can be defined for a single time step, with one-way data exchange between such models within a time step. This coupling will therefore also be external, less explicit and not be able to run in parallel. More detail on the simulator architecture is given in Chapter 3.

2.5 CONCLUSION

The literature survey clearly showed that the aim of this research should be realizable: to gain a fundamental understanding of external coupling of time-dependent multi-physics code systems, and to establish a platform to integrate and coordinate these types of analyses.

Three basic types of coupling schemes have been discussed with references. Stability problems for the intended external coupling with the existing CORBA-based simulator architecture can be expected, especially if it is going to be explicit in nature. Of the coupling methodologies discussed, external explicit, external but less explicit, parallel and indirect should be good candidates to implement and test. This should further be possible without too many code changes to the existing CORBA-based simulator architecture.

Examples of the external explicit ([8]), indirect ([8] and [9]) and parallel ([11]) couplings are presented in Section 2.3 and will be used as the basis for the work to follow.

3. SOFTWARE ARCHITECTURE

3.1 INTRODUCTION

The multi-physics integration platform established as part of this research is based on an existing but shelved CORBA-based simulator architecture. The prior development focused on integrating the time-dependent design and safety analyses and operational control environments used in PBMR (Pty) Ltd. It was possible to integrate multiple Flownex Nuclear and Simulink models with the operational control environment in a simulation scenario, scheduled in either real time or tight-loop mode. Some modifications were necessary to establish the CORBA-based simulator architecture as a multi-physics integration platform.

After modification, it proved to be an excellent platform to use for large integrated design and safety analyses simulation scenarios.

Modifications included:

- Removing the Supervisory Control and Data Acquisition (SCADA) or operational control interface.
- Simplifying the Graphical User Interface (GUI).
- Developing a TINTE interface to the simulator.
- Extending the simulation control and scheduling capabilities.
- Getting the modified architecture to operate in a stable and predictable manner.

For the purposes of this research, the modified CORBA-based simulator architecture will be called the Nuclear Engineering Analysis (NEA) Simulator. Installation and general usage of the NEA Simulator are discussed in [23].

The most important aspects of the software architecture will be discussed in more detail in the following sections. This includes the general simulator architecture; simulation time-step management; interfaces to the hosting software applications; and data logging, filtering and relaying, as described in Sections 3.2 to 3.5.

3.2 GENERAL SIMULATOR ARCHITECTURE

The NEA Simulator is built on top of the CORBA communication framework and runs on the Windows operating system. It utilizes a mixture of inherited and derived communication infrastructure components or services. These key services are listed in Table 1 and further explained in the following sections.

Table 1: NEA Simulator Infrastructure Components/Services

No.	Service	Amount Needed	Target Node/PC
1	Simulation Controller	One or more	Any PC
2	SimSetup Database	One only	Central application server
3	Name Service	One only	Central application server
4	Event Service	One only	Central application server
5	Scheduler Executive	One only	Any participating node/PC
6	Node Executive	One or more	All participating nodes/PCs

3.2.1 Communication Typology and Deployment

Figure 1 illustrates the communication typology of the NEA Simulator with an example, where the simulation set-up consists of four independent scenarios with their models deployed across two nodes or PCs.

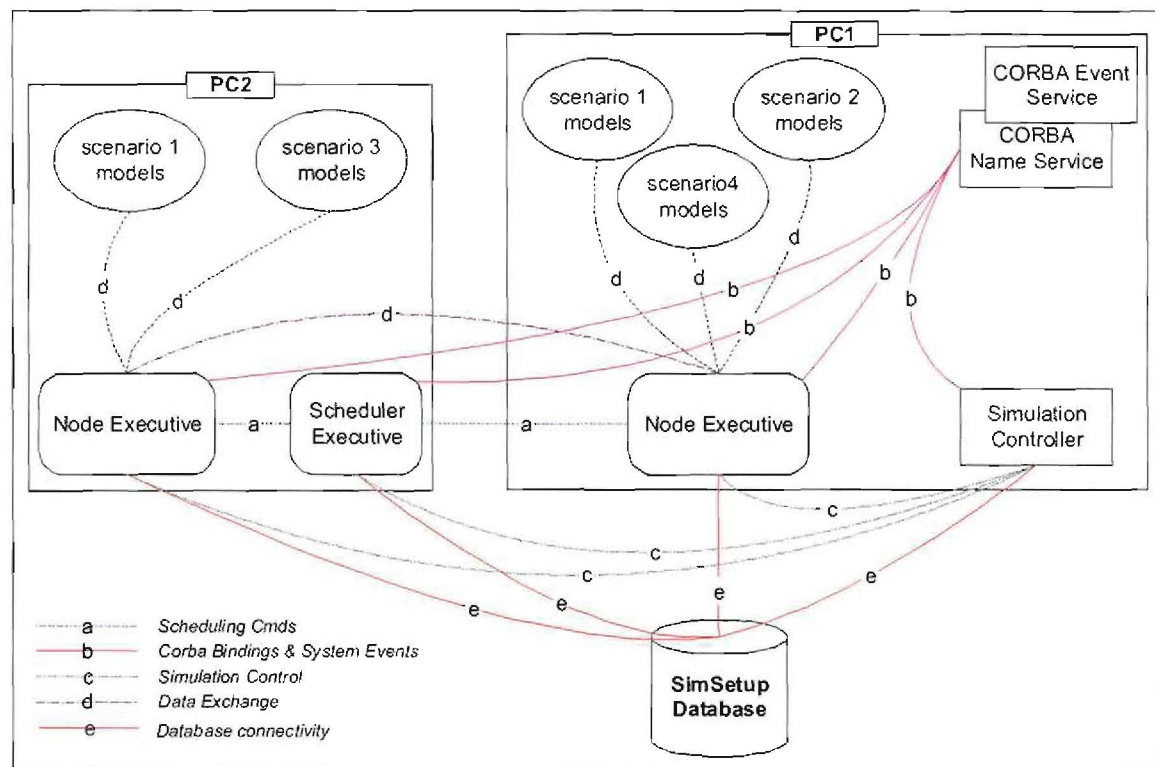


Figure 1: Simulation Set-up and Scenario Deployment

A common database is required for set-up, loading and initialization of the scenario to be simulated (lines 'e'). The Simulation Controller is used to perform configuration set-up and runtime control. To load a scenario, it first queries the database for the deployment information (lines 'e'). After this, it queries the CORBA Name Service to resolve the object interfaces provided by the Node Executive(s) and Scheduler Executive (lines 'b'). It then

communicates with the Node Executive(s) and Scheduler Executive via these interfaces and requests them to load the scenario selected by the user (lines 'c'). For each model to be loaded, a unique object interface is registered on the CORBA Name Service (lines 'b'). Each model interface sends either a load success or failure event to the Simulation Controller via the CORBA Event Service (lines 'b').

To run a simulation scenario, a command is issued to the Scheduler Executive from the Simulation Controller (lines 'c'). The Scheduler Executive performs all the synchronization of the simulation steps and data distribution (lines 'a'). Each physical model has a local interface to the Node Executive and can only communicate to other models via the Node Executive (s) (lines 'd'). Model interfaces can send error messages to the Simulation Controller via the CORBA Event Service (lines 'b').

During runtime, each physical model and hosting application will be started in a unique directory on the specified node by using the scenario name and model name as the unique identifier. This enables physical models and hosting applications to use the file system without interference from other models. After the simulation scenario has completed, all local file output will then be available in the unique runtime location. [10], [23]

3.2.2 Simulation Controller

The Simulation Controller is a GUI that enables simulation set-up and runtime control. User options for runtime control of a simulation scenario are (Figure 1, lines 'c'):

- Load.
- Initialize from default conditions or from saved restart conditions.
- Unload.
- Run a preset number of simulation cycles or until paused or stopped.
- Pause running.
- Resume running.
- Save restart information.
- Stop.

A simulation scenario comprises a hierarchical collection of simulation information. At the lowest level, tags are specified. Tags are the individual data items that will be exchanged between models, and have a name, description and engineering unit associated with them.

Models are next in line, and need to be configured with input and/or output tags as well as information about the physical model and associated software application that needs to be loaded and executed. Output tags must be unique across all models, but input tags may be

duplicated. Each model also has a special control tag, which would indicate to the Scheduler Executive whether or not the model must be actively stepped during runtime. To facilitate efficient configuration and deployment of physical models, a model repository is used (refer to Section 3.2.3).

Models are grouped together in a model set, with a model set being linked to a schedule, which in turn is linked to a scenario. The same model may therefore be used in many model sets, the same model set may be linked to different schedules, and the same schedule may be linked to different scenarios. The scenario will link its models to one or more nodes where a Node Executive is running. [10], [23]

3.2.3 Simsetup Database

A database common to and accessible by all simulation components is used to store the configuration information as set up in the Simulation Controller (Figure 1, lines 'e'). It also houses the model repository of all physical models that will be used during the simulation scenario. This feature allows easy configuration control of model versions, as it is managed in a central location and distributed to the chosen runtime node during the load state. [10], [23]

3.2.4 Name Service

The Name Service is a standard CORBA component utilized by the NEA Simulator to enable flexible distributed computing. It provides the principal mechanism through which most clients of an Object Request Broker (ORB) based system locate objects that they intend to use/make requests of (Figure 1, lines 'b').

The Name Service consists of one or more naming contexts, organized in a tree view type structure, called a naming graph. A naming context can define any amount of name bindings. Each name binding is a name-object association. Once an object is bound to a context in the Naming Service and the name binding is created, it becomes visible to any client on the data network. Such a client only needs to know the naming context and name of an object to be able to resolve it. Resolving a name is to determine the object interface associated with the name in a given context. Once the name is resolved, communication with the object becomes possible.

In the NEA Simulator, model, node executive and scheduler executive objects are bound into the Naming Service. Therefore, all components are visible on the data network and can communicate with each other as required once the names are resolved. This includes giving commands and exchanging data. [10], [23]

3.2.5 Event Service

The Event Service is a standard CORBA component utilized by the NEA Simulator to enable distributed event communication. It defines two roles for objects: the supplier role and the consumer role. Suppliers produce event data and consumers process event data.

Event data is communicated between suppliers and consumers by issuing standard CORBA requests (Figure 1, lines 'b'). The two approaches to initiating event communication are called the *push model* and the *pull model*. In the NEA Simulator, the push model is used. This model allows a supplier of events to initiate the transfer of the event data to consumers. Event communication is by means of generic operations that take a single parameter that packages the event data. A common structure for such a parameter was defined, and event data is then passed between registered suppliers and consumers, using this common definition.

Consumers, such as the Simulation Controller, can get immediate feedback from a supplier, such as a translator (refer to Section 3.4), regarding errors or state changes. For example, if the loading of a model times out because of an internal model to hosting software error, the corresponding translator will send a timeout error message to the Simulation Controller. On the other hand, if the model load command was executed successfully, a model loaded state change message will be sent to the Simulation Controller. [10], [23]

3.2.6 Scheduler Executive

At least one Scheduler Executive must be available for the simulation, but not more than one on a node. A Scheduler Executive can accommodate more than one schedule, i.e. it can schedule more than one scenario at a time.

The Scheduler Executive is responsible for issuing scheduling commands (step, stop and pause) to models (Figure 1, lines 'a'). It ensures that the various models are synchronized and will issue detailed error information on the error channel if any abnormal conditions occur. The user controls the execution of the simulator by issuing commands on the Simulation Controller, which in turn dispatches the commands to the scheduler for execution (Figure 1, lines 'c').

Each set of models that forms a single simulation scenario requires a scheduler model, which has a few predefined outputs and a single input. The idea behind the scheduler model is to provide time and simulation statistics to any other model that requires this input, and the single optional input is the next simulation step end time. This will enable an external model to determine what the length of the next simulation time step must be, thereby enabling variable simulation time steps for the scenario. If the scheduler model does not have this input, the user-defined simulation time step will be used. The scheduler model must be

configured in the Simulation Controller similar to the way in which any other model is configured, with the difference that it will be created automatically during load inside the Scheduler Executive. [10], [23]

Another feature implemented by the Scheduler Executive is the concept that a model can either be active or inactive during any part of the simulation scenario. It is automatically bound to all control tags that are configured for the simulation scenario. By default, all models are active, but an external logics model can toggle any model's control tag, thereby switching the corresponding model into and out of the simulation scenario during runtime. [10], [23]

3.2.7 Node Executive

Each participating node needs to have one Node Executive running for the simulation.

The Node Executive initializes and maintains the CORBA communication infrastructure for the node. The Simulation Controller sends a load command to the Node Executive to load models for a specific scenario. It is then each Node Executive's responsibility to determine from the database what models must be loaded on its node, load the hosting software with the appropriate models, register the models on the Naming Service, and release system resources after a run is complete (Figure 1, lines 'd').

A Node Executive can accommodate more than one scenario controlled by one or more Simulation Controllers at a time. The Node Executive sends detailed information on any abnormal conditions that occurs to the Simulation Controller via the event channel. A local log file is maintained on each node in case of communication failure. For each model loaded, the Node Executive subscribes to every other model that requires some or all of the models' outputs. [10], [23]

3.3 SIMULATION TIME-STEP MANAGEMENT

Time-dependent coupling and synchronization of neutron-kinetics and thermal-fluids codes need to be well defined. These codes usually employ implicit solvers and have their own schemes for selecting time steps. An easy approach would be to slave the one code to the other in terms of simulation time-step selection. In some transients, local power and flux can change a lot, and poor simulation time-step selection could lead to inaccurate or totally wrong time-dependent power behaviour. Thus, to slave the neutronics code can be fatal. On the other hand, if one attempts to slave the thermal-fluids code, rapid pressure changes due to fluid inventory changes could also be missed. More sophisticated coupling schemes than this are required. [12]

Similarly, the way in which simulation time steps will be managed in the NEA Simulator is important for integrated simulation scenarios, as different codes have different limitations and responses on simulation time steps. Various simulation time-step selection schemes have been devised before, and some examples are given in Section 3.3.1. The NEA Simulator caters for simulation time-step management on a global and local level. This scheme is discussed in Section 3.3.2.

3.3.1 Simulation Time-step Management in Other Schemes

An overview of other coupled code systems is given in Section 2.3. Details of their time-step selection schemes are discussed here.

The WKIND and Flownex Nuclear coupled code has a component external to both individual codes used to control the time-dependent simulation. It integrates file-based input and output from WKIND, and memory map data transfer from Flownex Nuclear. The internally generated time step from WKIND is used as the simulation time step, thus Flownex Nuclear is slaved to WKIND. [9]

In the previous coupling of TINTE and Flownex Nuclear, an external component is used to control the time-dependent simulation. Some of its functions are to manage data exchange between the two programs by means of memory maps and to actively aid in the convergence of the indirect coupling mechanism. It uses the internally generated temperature time step from TINTE (explained in more detail in Section 3.4.2.2) as the simulation time step and slaves Flownex Nuclear to it. [8]

In the TRAC-PF1/NEM code system, TRAC-PF1 uses thermal-fluids conditions and total power variations together with user-specified limits to calculate the time-step size. It also employs a variable time-step control algorithm for the 3D kinetics and is properly integrated with the thermal-fluids time-step selection algorithm, also referred to as a meshing scheme. Global reactor power and local neutronics changes are taken into account. [12]

The TRAC-BF1/NEM code system uses a multiple time-step marching scheme, whereby TRAC-BF1 can march several steps while NEM only marches one large time step. Similar to TRAC-PF1/NEM, a variable time-step algorithm is employed for the 3D kinetics and integrated with the thermal-fluid time-step algorithm. The time-step size is adjusted automatically based on time-dependent changes of global total power and local neutron flux. [12]

3.3.2 NEA Simulator

In the NEA Simulator, simulation time-step management is performed on a global and local level. Globally, the simulation time step is user controllable and advanced without any

knowledge of the participating models' internal time-step preferences. The local scheme interacts with the participating models' internal time-step management within the global simulation time step.

3.3.2.1 Global effects

Data exchange is performed at the end of each simulation time step, and thus forces explicitness and time delay to the integrated solution. For mutually dependent models, this parallel simulation architecture introduces an effective double simulation time-step delay. The explanation for this is as follows (refer to Figure 2):

When model A sends data to model B, it will arrive after one simulation time step. If B reacts to this data by having a further effect on A, the output of B will also only arrive after still another simulation time step at A. Thus the effective delay introduced by executing mutually dependent models in parallel is two simulation time steps.

Simulation time-step independence studies should be performed for the integrated simulation scenario. The effective simulation time-step delay will influence stability of the combined solution and thus force smaller simulation time steps, and the internal dynamics of the models during the transient will be proportional to the maximum simulation time step.

The user has control over how models are scheduled by configuring these options using the Simulation Controller. Each scheduled configuration is called a schedule and is stored in the simulation database. A schedule can have one or more intervals per cycle, with a cycle being equal to a single simulation time step. Models that are grouped together in a single interval will be executed in parallel with data exchange at the end of the interval, such as models A, B and C in Figure 2. Where time-dependent data distribution between models within a cycle is required, multiple intervals are used, such as model D in the second interval that could be a data logger.

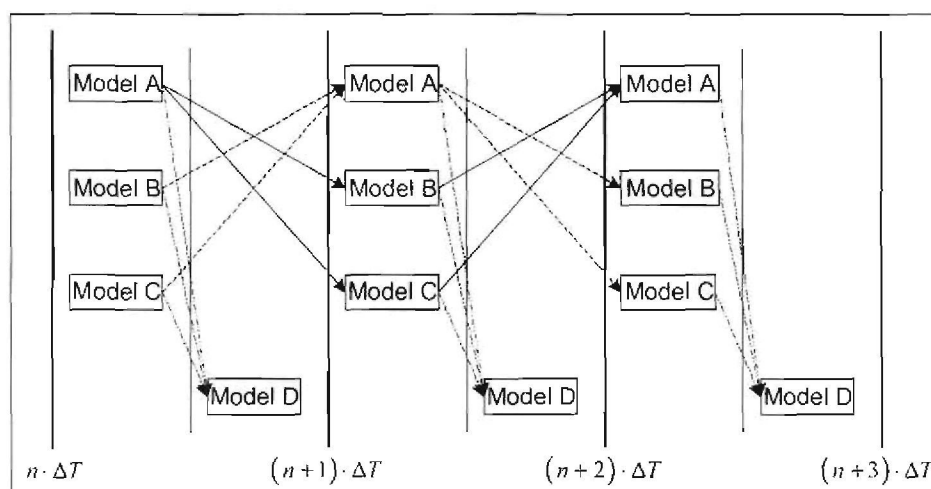


Figure 2: Simulation Timeline

As explained in Section 3.2.6, it is possible to use a fixed or variable simulation time step. Variable simulation time steps require a time step management model in the first interval, in which case it will be possible to issue fixed or variable simulation time steps. The logic of this model should be determined by the dynamic behaviour of the scenario being simulated. Any plant condition can be monitored, as long as the associated tag has been configured as an output for some model in the scenario.

3.3.2.2 Local effects

TINTE uses implicit neutronics and temperature solvers with the added feature of a built-in mechanism to determine its own neutronics, and temperature time-step lengths to optimize execution time [5]. It operates within minimum and maximum limits set as user input. TINTE commands are either entered via the console or a special TINTE input file denoted with a 'tn1' extension. After TINTE has been initialized so that the transient calculation can start, the first positive value of any command is the next intermediate end time. TINTE will run to this time by first taking small time steps, and then continuing to increase its time steps until the maximum limit is reached.

A TINTE time step consists of a single temperature time step and one or more neutronics time steps. The target for a temperature time step and the first neutronics time step will be set based on core dynamic conditions being monitored internally. Its basic philosophy is that a temperature calculation can always be completed if the neutronics has been successfully calculated. The neutronics calculation estimates the temperature gradient based on the power gradient at the end of its neutronics time step, and will recalculate everything with a smaller time step if the temperature gradient is too large or convergence has not been reached. If the first neutronics time step calculation in a temperature time step is unsuccessful, a smaller temperature time-step target will be set and the process will start over.

However, certain advert flow and heat transfer conditions will cause the TINTE temperature solver not to converge anymore. This is a result of an ill-conditioned solution matrix, even if the neutronics were calculated successfully. According to the manual [5], an efficient remedy for this is to limit the maximum time step that the TINTE temperature solver may take via console or tn1 input. After the troublesome piece of the transient has been completed, the limit can be relaxed gradually to let the execution of remaining transient speed up.

The amount of time steps that TINTE will take during a simulation time step is transparent to the user and the rest of the simulation scenario. The only active participation that needs to happen during a simulation time step is to ensure that the TINTE temperature solver will be

able to converge, without slowing down the entire simulation by being too conservative. Such a scheme is presented in Section 3.4.2.

Flownex Nuclear, on the other hand, uses an implicit pressure correction solution algorithm that is unconditionally stable and can accommodate variable or fixed simulation time steps. It will accept any target simulation time step on its external interface and perform a single time-step calculation for the required time period, but is potentially inaccurate in calculating fast dynamics when using large simulation time steps. Time-step independence studies with continually decreasing simulation time steps should be performed to determine the point at which the solution no longer changes significantly. Another feature of its time-dependent calculation is that Flownex Nuclear offers user-controllable relaxation parameters. It determines how much of the previous simulation time-step data is used and the time-dependent solution can be either fully implicit, fully explicit or anywhere in-between [6].

3.4 INTERFACES TO THE HOSTING SOFTWARE APPLICATIONS

Each type of model that will participate in the simulation needs an interface/translator that will facilitate low-level communication to its hosting software. It translates simulation, scheduling and data commands to and from the NEA Simulator into the specific API of the hosting software.

3.4.1 Basic Simulation Commands

The command set shown in Table 2 provides basic simulator functionality and is implemented by each translator. Not all commands are equally functional with regard to the different model types. For example, some hosting software combines load and init, some software does not have a stopped state, and some software cannot create a restart set. However, to be consistent, all translators implement the full command set, even if it results in an empty function call.

Table 2: Basic Simulation Commands

No.	Command	Description	Originator
1	Load	Load the hosting software and the model.	Simulation Controller
2	Init	Initialize the model. This will prepare the model so that the next command to the model could be a step command.	Simulation Controller
3	Snap	Snap an initial condition or restart set.	Simulation Controller
4	Close	Unload the model and the hosting software from memory.	Simulation Controller

No.	Command	Description	Originator
5	Step	Perform a single simulation time step.	Scheduler Executive
6	Stop	Stop the time-dependent calculations.	Scheduler Executive

3.4.2 TINTE Link

TINTE is a legacy code created in FORTRAN 77 with limited FORTRAN 90 coding. It does not have an API; therefore one was created from scratch.

3.4.2.1 Coupling methodology

The chosen method for data communication was to use memory map transfer, similar to most of the existing translators in the NEA Simulator and to that employed in [8]. The Windows piping mechanism was chosen to send console commands to TINTE and to display its console response on a redirected Windows console, also similar to that used in [8].

The major differences between the TINTE link translator and the interface developed in [8] are:

- In addition to the translator class, a dedicated wrapper program was created to implement the Windows redirected piping mechanism.
- Two bidirectional memory maps are utilized: one for data communication to TINTE and one for commands to the wrapper program.
- The normal mechanism for controlling a TINTE transient via a tn1 file [5] is not used. Instead, all TINTE transient commands are interpreted and passed to the redirected TINTE console for each simulation time step. No future information about any transient is therefore issued to TINTE beyond the scope of the immediate simulation time step. All TINTE inputs are logged to a file for future use. (Refer to Section 3.4.2.5.)
- The internal TINTE time step is determined by TINTE itself, but always coincides with the global simulation time step by virtue of passing it a time to run to that is equal to the end of that current simulation time step.
- A scheme was implemented to help the TINTE temperature solver converge during advert flow and heat transfer conditions, based on certain conditions being monitored by the TINTE link translator. (Refer to Section 3.4.2.2.)
- TINTE is always initialized from a real-world situation restart set, as performing a steady state will only produce a real-world reactor state at time zero. In this way it is possible to bring the reactor to a different state and record a restart set either for use as a new initial reactor state model, or as a different initial condition for the specific simulation scenario.

3.4.2.2 Local control of TINTE temperature solver time steps

The simple solution would be to limit temperature time steps to a single small value to ensure convergence, but this would hamper general execution speed of the integrated simulation scenario.

Temperature time-step limits based on mass flow, control rod and maximum fuel temperature gradients are sent to TINTE on a continuing basis. This has the effect that many TINTE time steps may be taken during a single simulation time step under advert conditions, but when the conditions change, the TINTE temperature solver is allowed to take longer time steps up to the simulation time step.

The above-mentioned gradients and corresponding temperature time-step limits, shown in Table 3, were found by trial and error and fine-tuned with many simulations where these gradients were extreme.

Table 3: Temperature Time-step Limits and Monitored Gradients

No.	Mass Flow (kg/s/s)	Control Rod (cm/s)	Average Fuel Temperature (°C/s)	Temperature Time-step Limit (s)
1	< 1	< 0.05	< 0.025	50
2	≥ 1 and < 2	≥ 0.05 and < 0.1	≥ 0.025 and < 0.05	10
3	≥ 2 and < 4	≥ 0.1 and < 0.25	≥ 0.05 and < 0.1	2
4	≥ 4 and < 8	≥ 0.25 and < 0.4	≥ 0.1 and < 0.2	0.5
5	≥ 8 and < 10	≥ 0.4 and < 1.02	≥ 0.2 and < 0.3	0.1
6	≥ 10 and < 13	≥ 1.02 and < 5.5	≥ 0.3 and < 0.5	0.025
7	≥ 13 and < 20	≥ 5.5 and < 50.5	≥ 0.5 and < 20	0.015
8	≥ 20 and < 300	≥ 50.5 and < 100	≥ 20 and < 200	0.01
9	≥ 300	≥ 100	≥ 200	0.005

A side effect of using this technique was noted: changes in temperature time-step limit result in discontinuities in the maximum fuel temperature. However, this symptom has not been witnessed in any of the other TINTE outputs. To smooth this effect, a second-order low-pass filter (refer to Section 3.5) was introduced to filter the calculated limit before being applied to TINTE. The minimum limit is first calculated according to the table and then filtered. However, the limit is allowed to decrease by any amount in a single simulation time step, without filtering, if the increase in gradient is too large. Filtering the limit when there is a sudden increase in the gradient causes the limit to be applied too late. The result is a smooth

maximum fuel temperature curve in the face of fluctuating gradients and simulation time steps.

When applying this technique for a variable simulation time-step transient, the typical influence on the temperature time-step limit is as shown in Figure 3. Note that when the simulation time step is smaller than the calculated temperature time-step limit, the effective temperature time-step limit becomes equal to the simulation time step.

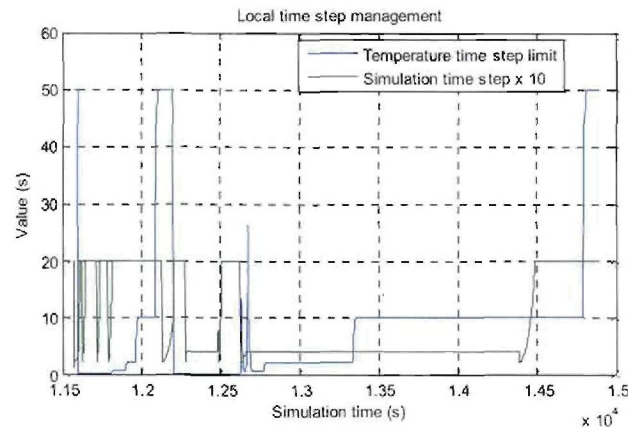


Figure 3: Local Time-step Management

The absolute values of the gradients used in determining the temperature time-step limit for the above-mentioned case are shown in Figure 4. The transient consisted of a slow control rod withdrawal, constant period and a slow control rod insertion. Note the presence of a fairly large temperature gradient long after the control rod transient has been finished, which caused the temperature time step only to be increased slowly.

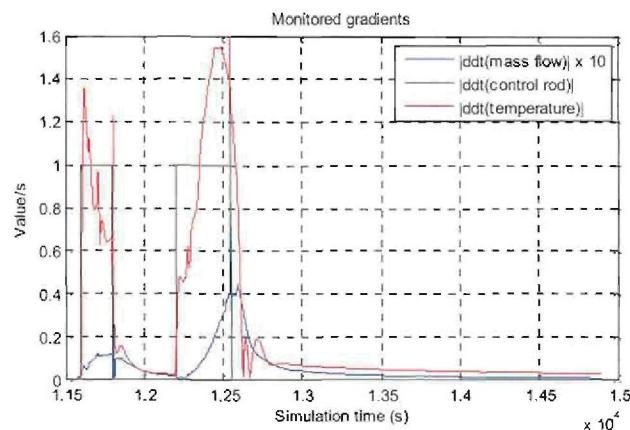


Figure 4: Monitored Gradients

3.4.2.3 Code changes

A separate FORTRAN 90 signalling module was created to house the required interfacing code to the wrapper program. Limited code changes were necessary within the TINTE controlling subroutine. It consisted of a few function calls that open and close the signalling

and update output data to the memory map. Some status messages are also echoed to the console output.

The signalling becomes active by executing TINTE with a command line switch `-NAME XYZ`, with XYZ being the name of the memory map, which must exist prior to starting TINTE. If started in this way, the new module will perform verification checks to ensure the memory map interface is valid. The required output data must be specified inside the memory map in any order, and the signalling module will create a corresponding internal list of output data. The memory map will be updated after each temperature time step.

TINTE model input tags can be specified when configuring the model in the NEA Simulator and can be divided into two categories. Firstly, there are those that can affect the TINTE transient, and secondly there are those that will control the output that is made available on the memory map from the signalling module. As mentioned, all TINTE transient commands are interpreted and passed to the redirected TINTE console for each simulation time step. The normal TINTE console output is then redirected back to the wrapper program's console.

3.4.2.4 Available inputs and outputs

TINTE tags are preprogrammed and not free format, but can be set up in any sequence. Valid TINTE model tags are given in Table 4 and Table 5.

Table 4: TINTE Input Tags

No.	Tag Name	Description
1	Ti_RodPosition	Control rod position.
2	Ti_GasTempIn_R	Reactor inlet temperature.
3	Ti_MassFlowIn_R	Reactor inlet mass flow.
4	Ti_PressureOut_R	Reactor outlet pressure.
5	Ti_GasTempIn_C	CBCS inlet temperature.
6	Ti_MassFlowIn_C	CBCS inlet mass flow.
7	Ti_PressureOut_C	CBCS outlet pressure.
8	Ti_TemperatureColumn	Mesh column number to provide output temperatures for.
9	Ti_FluxColumn	Mesh column number to provide output fluxes for.

Table 5: TINTE Output Tags

No.	Tag Name	Description
1	Ti_ROT	Reactor outlet temperature.
2	Ti_FissionPower	Reactor fission power.
3	Ti_DecayHeat	Reactor decay heat.
4	Ti_TotalPower	Reactor total power.
5	Ti_K_eff	K effective.
6	Ti_AvgFuelTemp	Average fuel temperature.
7	Ti_MaxFuelTemp	Maximum fuel temperature.
8	Ti_AvgModeratorTemp	Average moderator temperature.
9	Ti_Xenon	The global ratio of neutron absorption by poisons to fission neutron production as the sum for the isotopes Xe-135, Sm-149, Sm-151 and Gd-157 [24].
10	Ti_TinteCycles	Amount of TINTE temperature cycles completed for the simulation time step.
11	Ti_TinteTime	TINTE time at the end of a TINTE temperature time step.
12	Ti_Reactivity	Dynamic reactivity [24]. In the mode that TINTE is used together with the NEA Simulator, this value has no meaning.
13	Ti_PressureIn_R	Reactor inlet pressure.
14	Ti_MassFlowOut_R	Reactor outlet mass flow.
15	Ti_PressureIn_C	Core barrel cooling channel inlet pressure.
16	Ti_MassFlowOut_C	Core barrel cooling channel outlet mass flow.
17	Ti_TemperatureOut_C	Core barrel cooling channel outlet temperature.
18	Ti_Flux_Col_Out	Actual mesh column number the fluxes have been provided for. This is necessary due to the time lag created by the parallel simulator architecture.
19 – 56	Ti_Flux_01 – Ti_Flux_38	Fluxes for individual mesh cells from the top of the neutronics mesh for the selected column.
57	Ti_Temperature_Col_Out	Actual mesh column number the temperatures have been provided for. This is necessary due to the time lag created by the parallel simulator architecture.
58 – 111	Ti_Temperature_01 – Ti_Temperature_54	Temperatures for individual mesh cells from the top of the temperature mesh for the selected column.

3.4.2.5 Validation

Validation of the code changes is facilitated by the coupling philosophy. All TINTE inputs, including the initial start-up, are logged to a file in its local runtime directory as the simulation scenario progresses. This file can be used as tn1 type input to the unmodified TINTE, and to the modified TINTE when starting it without the optional –NAME switch. The resulting output files could then be compared and should be an exact match.

The modified TINTE tested favourably on all counts.

3.4.3 Flownex Nuclear Link

Flownex Nuclear is a modern code and has a standard way of communicating to external programs. It traditionally used a memory map for data transfer, and Windows events for synchronization. The latest release provides an additional object interface which, for example, can be used to create restart sets and to initialize from. However, this latest functionality has not yet been implemented in the translator.

The corresponding translator in the NEA Simulator was existing functionality, but needed enhancement and verification, as there had subsequently been multiple releases of Flownex Nuclear. Some minor code changes in the translator were necessary, for example, the following have changed: the definition of the memory map structure and contents, as well as some finer points on synchronization.

All Flownex Nuclear inputs and outputs to and from the translator are logged to its local runtime directory as the simulation scenario progresses.

3.4.4 Simulink Link

Matlab [7] with Simulink is a modern code and has a standard method of communicating to external programs. In the NEA Simulator, this was combined with a memory map for data transfer, and Windows semaphores for synchronization.

The corresponding translator in the NEA Simulator was existing functionality, but needed enhancement and verification, as there had subsequently been multiple releases of Simulink. For example, the specific release of Simulink includes code interface files that need to be linked into the Node Executive when producing the executable. Some of the enhancements included the concept of having a compulsory ModelInit.m file that can be used to set up Matlab environment variables or to run additional Matlab files during model initialization.

The Matlab workspace is updated after every cycle, and all internal variables that are saved to the workspace can be monitored as the simulation scenario unfolds. At the end of the simulation, the workspace is saved automatically to a unique file in its local runtime directory.

In addition, all Simulink commands issued by the translator are logged to its local runtime directory as the simulation scenario progresses.

3.4.5 Generic Link

The Generic translator was originally provided to afford enthusiasts the opportunity to code their own application that can fit into the NEA Simulator framework and take part in the simulation scenario like any other model. The corresponding translator in the NEA Simulator was existing functionality and still worked well.

The data logging, filtering and relaying application discussed in Section 3.5 interfaces to the NEA Simulator via the Generic translator.

3.5 DATA LOGGING, FILTERING AND RELAYING

As part of the NEA Simulator functionality, there was a need to log any chosen tag available in the communication infrastructure during the simulation scenario. A logical progression of this requirement was to be able to relay data without change, and to provide a filtering capability for noisy data.

3.5.1 Data Monitor

The Monitor application is newly developed and configured similar to any other model participating in the simulation scenario. Two types of outputs are defined: filtered and relayed. This application does not have its own outputs, and can only filter and/or relay input tags and present them as output tags with '_Relayed' or '_Filtered' postfixes. All input and output tags will also be echoed to the main application window for quick reference purposes, and will be logged to two separate files in the local runtime directory if opted by the user. These files can be monitored as the simulation scenario unfolds.

The Data Logging Filtering and Relaying application is usually configured in its own interval after the primary interval. In this way, all data generated by any model for that simulation time step can be logged, relayed or filtered. Any output tag that needs to be relayed to the same model as input now becomes viable, as a model cannot be configured to have the same tag as input and output. Global or unique characteristics for the second-order low-pass filters (refer to Section 3.5.2) can be defined per input tag that needs to be filtered.

The Data Logging Filtering and Relaying application communicates to the NEA Simulator via the Generic translator.

3.5.2 General Filter Implementation

Due to noise being present on some signals, second-order low-pass filtering capability was added to the NEA Simulator. The continuous s -domain transfer function $H(s)$ of the second-order low-pass filter has the following form [25]:

$$H(s) = \frac{K\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \quad (3.1)$$

with

ω_n	natural or cut-off frequency in rad/s
K	Gain
s	Laplace operator
ζ	Damping coefficient

For practical application in the NEA Simulator, the damping coefficient was chosen as 1 to ensure the fastest filter response without any overshoot if, say, a step signal was filtered. A gain of 1 was chosen not to distort the closed-loop behaviour. A low-pass filter would be analogous to a grounded mass-spring-damper combination in series, except that a force applied to the mass would be translated into a distance. With the low-pass filter, the output would be exactly equal to the input in steady state.

The bilinear transformation, where $1/s = T(1+z^{-1})/(2(1-z^{-1}))$, was used to transform the continuous s -domain filter to a z -domain filter that could be implemented in a discrete sampled data system [26]. After transformation, the filter has the following form:

$$\begin{aligned} H(z) = \frac{Y(z)}{X(z)} &= \frac{K\omega_n^2(1+z^{-1})^2}{\omega_n^2(1+z^{-1})^2 + 2\zeta\omega_n\left(\frac{2}{T}(1-z^{-1})\right)(1+z^{-1}) + \left(\frac{2}{T}(1-z^{-1})\right)^2} \\ &= \frac{\hat{a}_0 + \hat{a}_1 z^{-1} + \hat{a}_2 z^{-2}}{\hat{b}_0 + \hat{b}_1 z^{-1} + \hat{b}_2 z^{-2}} \end{aligned} \quad (3.2)$$

with

T	Sampling time
-----	---------------

The natural frequency was chosen in the range $2\pi(1/T) \leq \omega_n \leq 2\pi(10/T)$, where $\omega_n = 2\pi f$ with $f = FF/T$ being the natural frequency in Hz and FF being the filter factor.

Equation (3.2) can now be directly programmed as follows:

$$Y(z)(\hat{b}_0 + \hat{b}_1 z^{-1} + \hat{b}_2 z^{-2}) = X(z)(\hat{a}_0 + \hat{a}_1 z^{-1} + \hat{a}_2 z^{-2})$$

Discrete form :

$$\hat{b}_0 y(k) + \hat{b}_1 y(k-1) + \hat{b}_2 y(k-2) = \hat{a}_0 x(k) + \hat{a}_1 x(k-1) + \hat{a}_2 x(k-2) \quad (3.3)$$

$$y(k) = \frac{1}{\hat{b}_0} (\hat{a}_0 x(k) + \hat{a}_1 x(k-1) + \hat{a}_2 x(k-2) - \hat{b}_1 y(k-1) - \hat{b}_2 y(k-2))$$

3.6 CONCLUSION

The CORBA-based simulator architecture provided by PBMR (Pty) Ltd proved to be very flexible. As a fully fledged general-purpose simulator, it enabled the NEA Simulator to be developed in a relatively short time.

The operational control interface was removed and the GUI was simplified. A new translator and wrapper program for TINTE was successfully developed and integrated into the NEA Simulator, and the modified architecture was made to operate in a stable and predictable manner. Lastly, the simulation control and scheduling capabilities were enhanced to make the NEA Simulator a practical analysis tool.

Dedicated coupling between TINTE and Simulink or between TINTE and Flownex Nuclear would have been possible and a lot quicker than going through all the effort to develop the NEA Simulator. In this case, however, large integrated and distributed simulations would not have been possible.

Currently, the NEA Simulator is actively being used in operational control algorithm development and testing in PBMR (Pty) Ltd, where TINTE and Simulink are employed. It is also nearly production-ready to be used by a larger user base in PBMR (Pty) Ltd for simulation scenarios where TINTE, multiple Flownex Nuclear models and multiple Simulink models are integrated.

4. INTEGRATED SIMULATION

4.1 INTRODUCTION

Multiple detailed models are utilized to model the important thermal-fluid and time-dependent neutronics phenomena of the entire plant. To simulate and control all plant modes of operation [27] involving the reactor and transitions between the modes with high fidelity, a large integrated model would be needed. Integration of all these detail models into a single model to be executed by a single hosting application would yield an enormous model. It would theoretically still be solvable, but impractical with regard to time to set it up, to validate it, and to use it for transient simulations.

With the NEA Simulator, the models can be integrated externally, retain their validation status and be deployed over several computing nodes during runtime for optimized execution speed. This integrated simulation scenario could then potentially be used to simulate and control the plant modes of operation. Certain plant modes of operation would, however, cause some models to experience zero flow conditions, which would pose problems to the thermal-fluids solvers. This problem could potentially be overcome by utilizing a logics model to switch the models that experience near zero flow conditions in and out of the simulation scenario.

The MPS contains the primary thermal-fluids loop. Figure 5 shows the detailed Flownex Nuclear models of the MPS. These models are the Core Conditioning System (CCS), Core Barrel Cooling System (CBCS), reactor, PCU and Helium Inventory Control System (HICS).

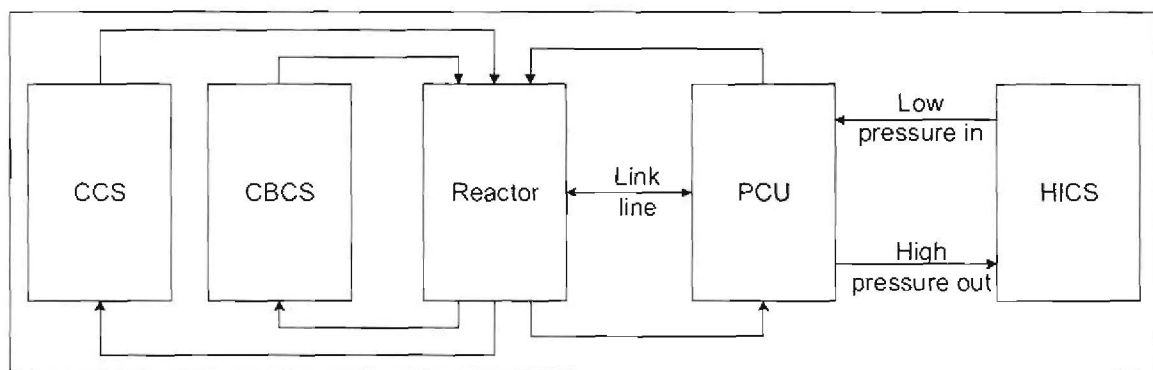


Figure 5: Main Power System Models

Due to complexity, scaled down Flownex Nuclear model versions of the MPS were created that generally contain one or two detailed sub-component models, with the others simplified or omitted. The MPS model used in this research contains detailed reactor and PCU models, with a simplified CBCS included in the reactor model. The reactor model is a multidimensional networked thermal-flow model to account for the thermal-flow behaviour of the reactor core and core structures. It includes simplified time-dependent neutronics

calculations that are implemented with point kinetics, coupled to the thermal-fluids calculations, and mutually dependent on the thermal-fluids calculations.

Detailed time-dependent neutronics calculations are performed with TINTE, which includes its own thermal-fluids calculations. However, the Flownex Nuclear reactor model provides more advanced thermal-fluids calculations that include time-dependent compressible fluid flow and detailed temperature profiles in the metal structures surrounding the core.

A logical application of the NEA Simulator would be to set up a simulation scenario that retains the best aspects of each of the reactor models. To reach the goal of simulating all plant modes and transitions involving the reactor on a continuous basis, it would also be beneficial to split the Flownex Nuclear MPS model into the reactor and PCU. This would enable the integrated simulation of start-up from shutdown to standby to power operation modes [27]. The starting configuration would be where the CCS is cooling the reactor with the PCU non-operational and experiencing zero flow conditions. At some point, forced helium flow would be channelled through the reactor from the PCU. Permitting certain reactor neutronics and PCU thermal-fluid conditions, the CCS would then be taken out of service to complete the start-up to power operation mode.

This research focused on splitting the Flownex Nuclear MPS model into the reactor and PCU, as well as on the coupling of TINTE with Flownex Nuclear. Setting up a simulation scenario to simulate all plant modes and transitions involving the reactor on a continuous basis was not part of this research. However, all the building blocks required for such a task have been prepared and positive results were achieved. The following sections form a logical progression to show that it is possible to achieve these goals.

4.2 EXTERNAL COUPLING OF FLOWNEX NUCLEAR MODELS

To enhance the success rate of a TINTE/Flownex Nuclear coupling, the behaviour of an all Flownex Nuclear coupled Reactor/PCU configuration can be investigated. This would also form the basis of coupling multiple Flownex Nuclear models towards a large integrated simulation scenario.

4.2.1 Methodology

To solve a steady state for a closed-loop model, one either needs a reference mass flow rate or a reference pressure to be specified anywhere in the closed loop. Once the transient starts, the fixed reference can be released and the solution will be influenced by the system boundary conditions. An open-loop model needs to have a pressure, temperature and mass flow rate specified as boundary conditions with pressure and mass flow rate at opposing sides. In this case, a reference pressure inside the network is optional.

The coupling methodology for the Flownex Nuclear Reactor/PCU configuration is shown in Figure 6. A reference closed-loop MPS model is used and broken at chosen interfacing nodes so that these nodes will be duplicated in both models. The reactor model interfaces to the PCU model at three nodes: the reactor inlet, reactor outlet and a pressure equalizer link line between the reactor and PCU. Opposing boundary conditions are then set up at these nodes, for example pressure and temperature on one side and mass flow on the other. An optional Simulink model can be used for transient control, logics or operational control.

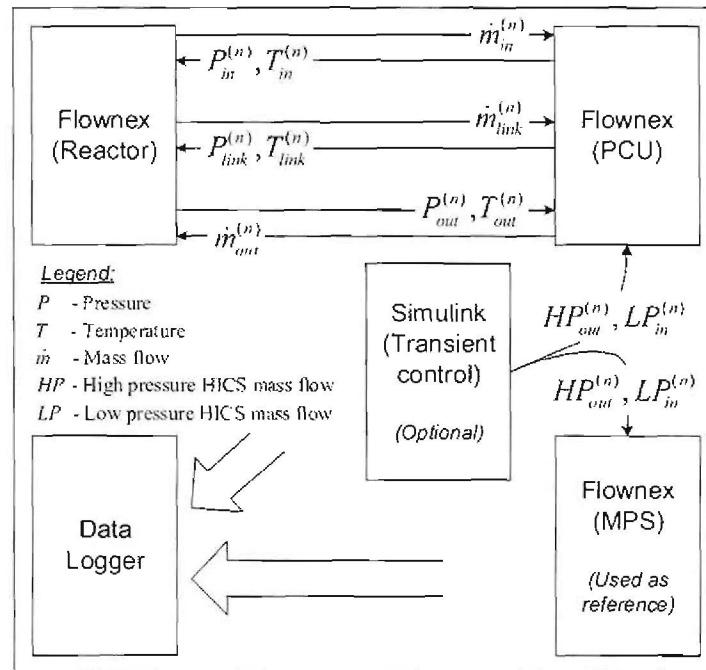


Figure 6: Flownex Nuclear External Coupling Scenario

Initial values for these boundary conditions are copied from a steady-state solution from the closed-loop reference MPS model. The data exchange arrows in Figure 6 originate from the node where the values are calculated and point to the node where the boundary conditions are applied. These boundary conditions will then be updated once the time-dependent solution starts.

Further detail is required on exactly how these interfacing nodes are treated in this research. Interface nodes are chosen to represent a desired physical location. Each interface node is only connected to a single component, even if it means introducing an unobtrusive dummy pipe component and additional node at a three-way node junction. This will then create single or series flow lines either side of the node in question, and can then be split as shown in Figure 7 (A). The arrows indicate the node where the values are calculated and point to the node where the boundary conditions are applied.

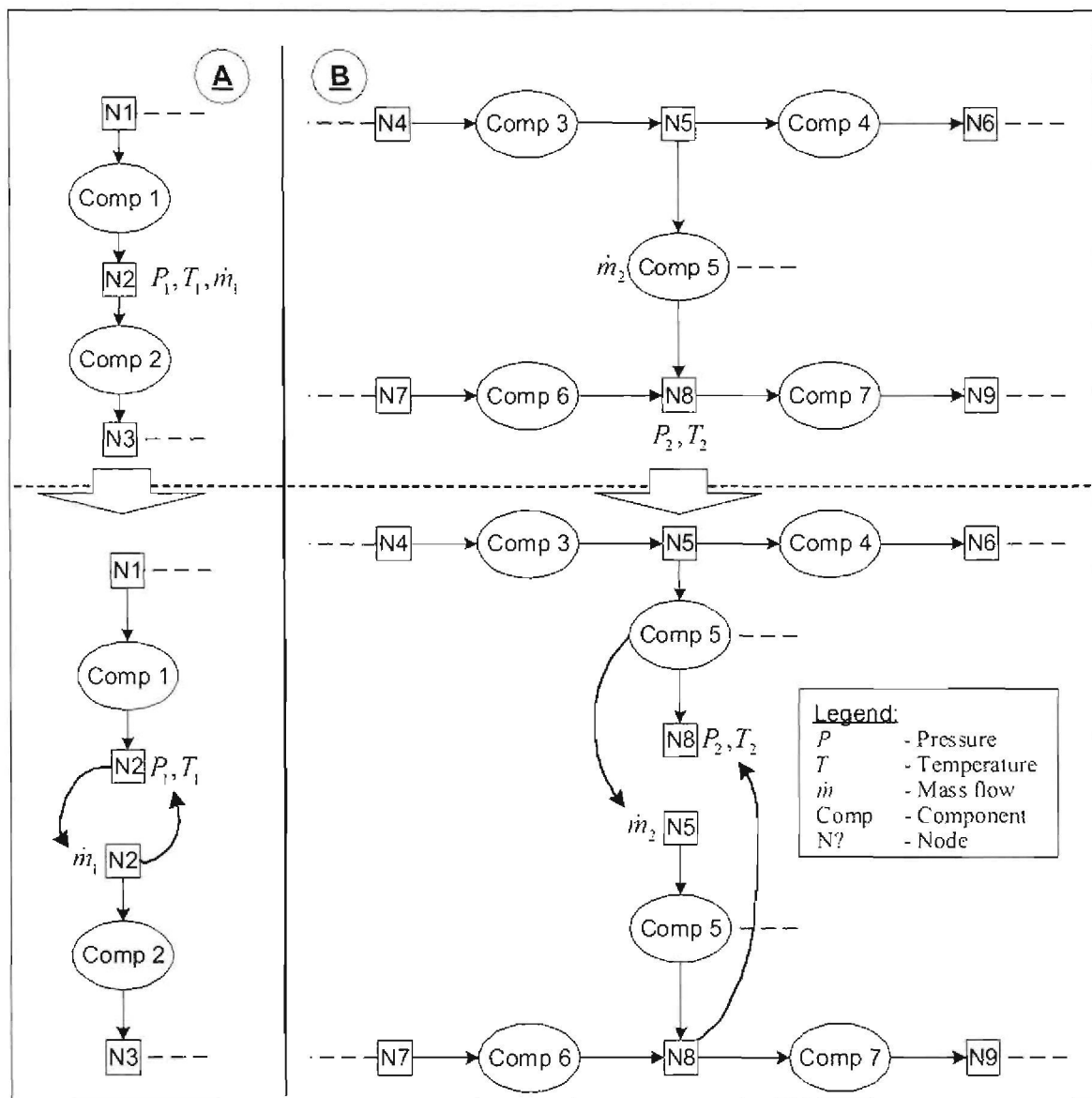


Figure 7: Flownex Nuclear Model Splitting Philosophy

The link line between the reactor and PCU warranted special attention, as the required split falls on a component and not a node (Figure 6, link and Figure 7 (B), component 5). The flow in this component is usually zero during steady transient states as it acts as a pressure equalizer, and one solution was to duplicate the link line and adjoining nodes in both models.

4.2.2 Steady-state Equilibrium Time-step Behaviour

The steady-state equilibrium time-step behaviour was investigated for two types of transients: fixed pressure and solved pressure. The fixed pressure case has a reference pressure somewhere inside flow network, and during the transient this pressure can be changed. Mass flow in the system will be the result of this pressure. For the solved pressure case, the fixed reference is released once the transient starts, and the solution is influenced by the system boundary conditions. The simulation time step was used as the independent

variable to perform the steady-state equilibrium time-step study. These two cases are discussed in Sections 4.2.2.1 and 4.2.2.2.

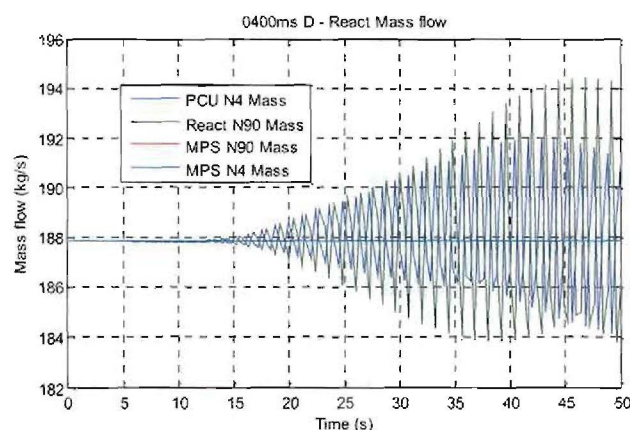
4.2.2.1 Fixed pressure

The first case was investigated by using the reactor/PCU combination of Figure 6, with the schedule shown in Table 6. It was configured with only one interval (see Section 3.3.2.1) and all dependent models in the same interval. Note the addition of the scheduler model as discussed in Section 3.2.6.

Table 6: Schedule Configuration for the Simulation Scenario of Figure 6

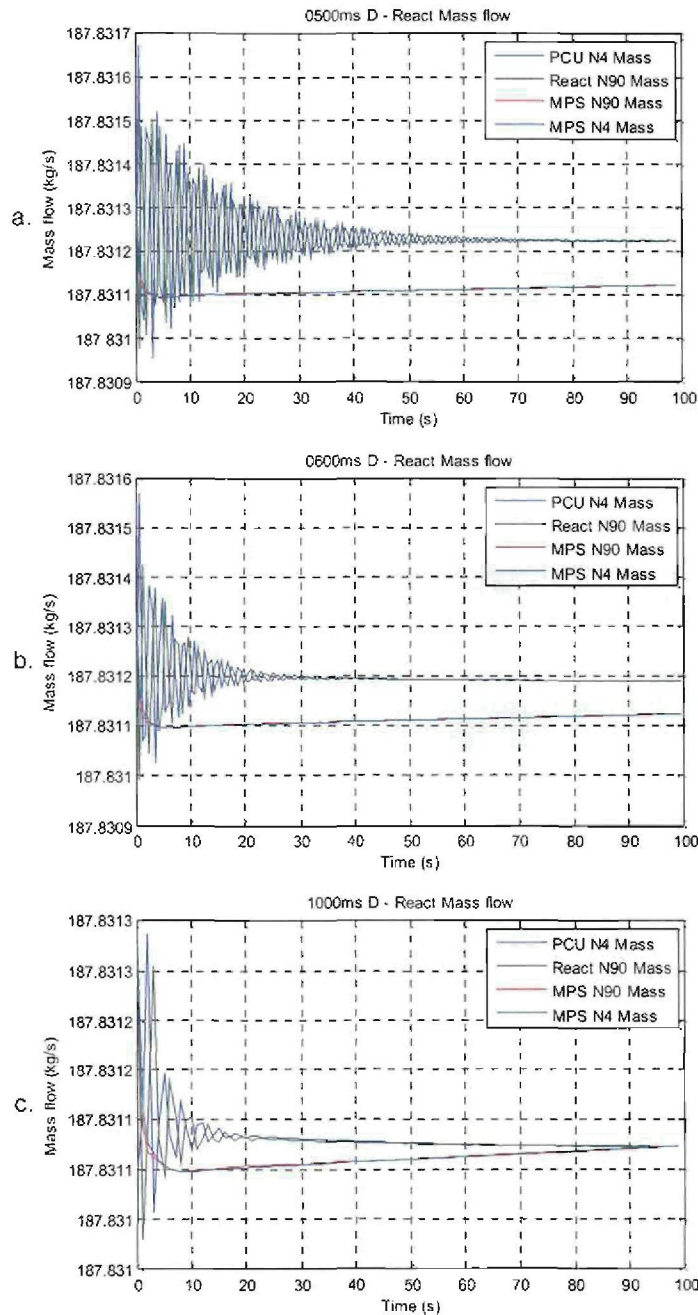
Slot	Simulation Time Step
	Interval 1
1	Reference MPS model
2	Reactor model
3	PCU model
4	Scheduler model

Instabilities in the external coupling were found when reducing the simulation time step. This behaviour was not expected, as reducing the simulation time step should make a dynamic system, such as this one, more stable. The mass flow calculated by both models was used as an indicator of stability and is shown in Figure 8 and Figure 9 for increasing the simulation time steps. (Signals/figure legends used and their meanings are shown in Table 7.) After the time-dependent solution starts, a steady equilibrium transient state is achieved when the reactor inlet and outlet mass flows are equal and stable. As can be seen, the coupled system's stability improved when enlarging the simulation time step. From top to bottom, the simulation time steps are 400 ms, 500 ms, 600 ms and 1 000 ms.



Note: Both reference signals, 'MPS N90 Mass' and 'MPS N4 Mass', are situated on top of each other just below 188 kg/s.

Figure 8: Flownex Nuclear Time-step Behaviour – Fixed Pressure



Note: Both reference signals, 'MPS N90 Mass' and 'MPS N4 Mass', are situated on top of each other starting at 188.8311 kg/s.

Note: Both reference signals, 'MPS N90 Mass' and 'MPS N4 Mass', are situated on top of each other starting at 188.8311 kg/s.

Note: Both reference signals, 'MPS N90 Mass' and 'MPS N4 Mass', are situated on top of each other starting at 188.8311 kg/s.

Figure 9: Flownex Nuclear Time-step Behaviour – Fixed Pressure (Continued)

Table 7: Signal Descriptions for Figure 8 and Figure 9

Signal Name	Description
React N90 Mass	Reactor inlet mass flow, calculated by the reactor model.
PCU N4 Mass	Reactor outlet mass flow, calculated by the PCU model.
MPS N90 Mass	Reactor inlet mass flow, calculated by the reference MPS model.
MPS N4 Mass	Reactor outlet mass flow, calculated by the reference MPS model.

4.2.2.2 Solved pressure

The second case was investigated by using a similar set-up to that described in Section 4.2.2.1; reactor/PCU combination of Figure 6 with the schedule shown in Table 6.

The steady equilibrium transient state for the solved pressure case was more difficult to reach. It produced pronounced settling times and instabilities when reducing the simulation time step. The mass flow calculated by both models was again used as an indicator of stability and is shown in Figure 10 and Figure 11 for increasing simulation time steps. (Signals used and their meanings are shown in Table 8.)

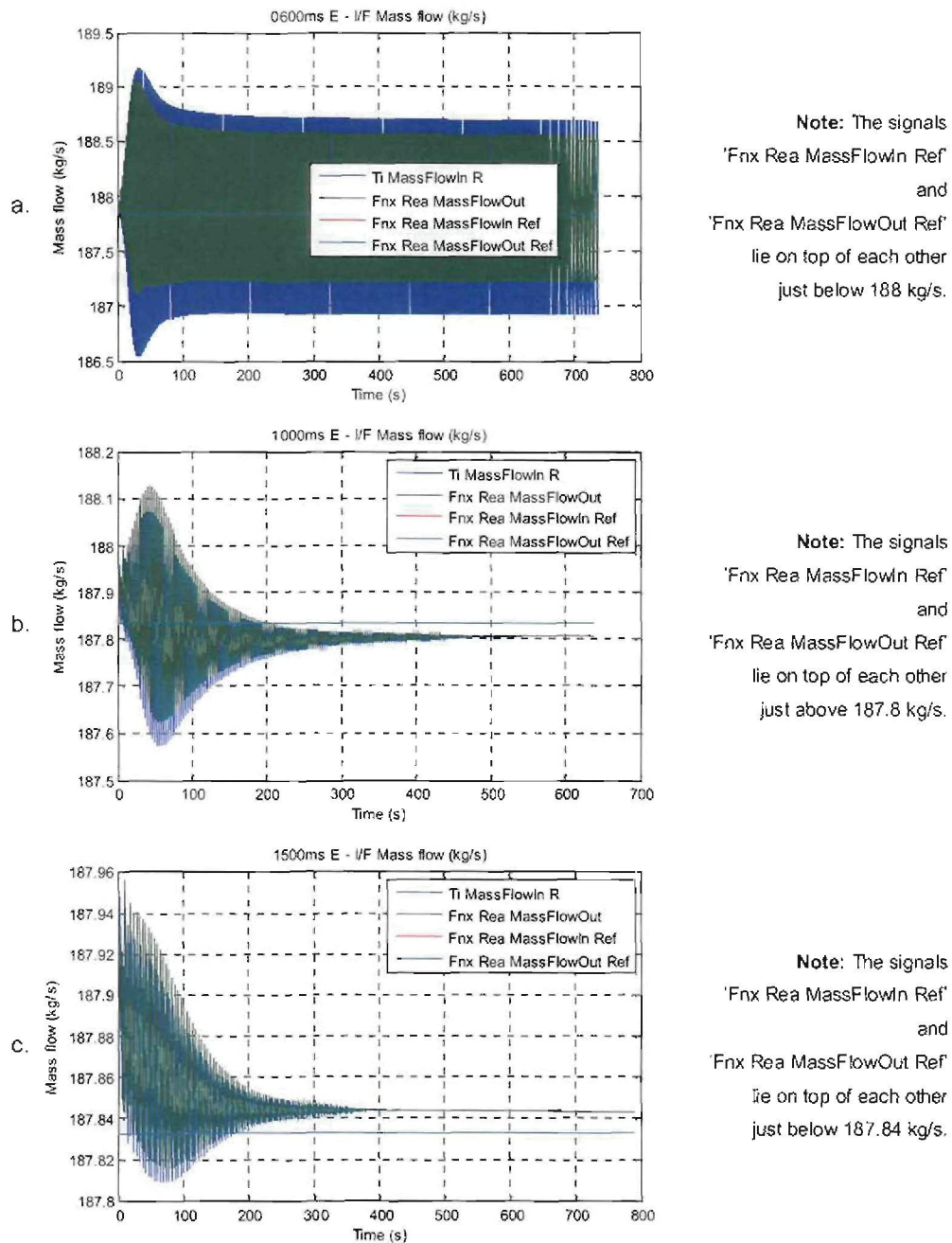


Figure 10: Flownex Nuclear Time-step Behaviour – Solved Pressure

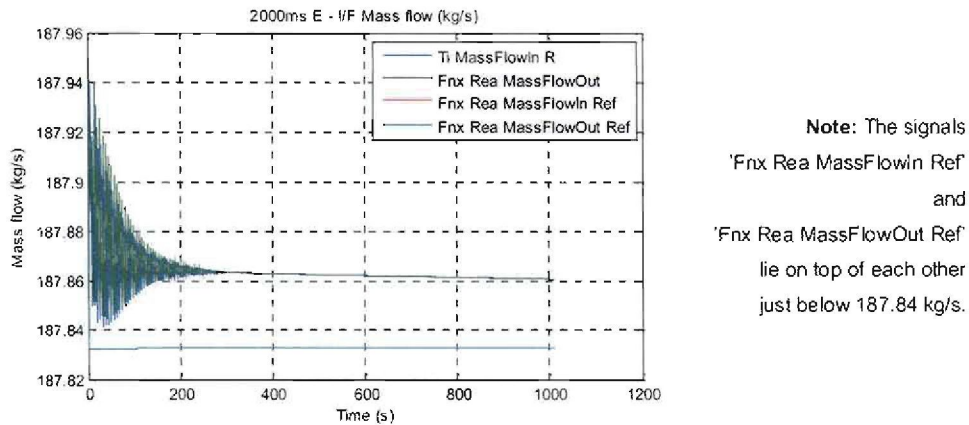


Figure 11: Flownex Nuclear Time-step Behaviour – Solved Pressure (Continued)

From top to bottom, the simulation time steps are 600 ms, 1 000 ms, 1 500 ms and 2 000 ms, and similar to the fixed pressure case, this behaviour was not as expected. For 1 000 ms, equilibrium was only achieved at 450 s into the transient compared to 45 s for the fixed pressure case.

Table 8: Signal Descriptions for Figure 10 and Figure 11

Signal Name	Description
Fnx Rea MassFlowOut	Reactor outlet mass flow, calculated by the PCU model.
Ti Rea MassFlowIn R	Reactor inlet mass flow, calculated by the reactor model.
Fnx Rea MassFlowOut Ref	Reactor outlet mass flow, calculated by the reference MPS model.
Fnx Rea MassFlowIn Ref	Reactor inlet mass flow, calculated by the reference MPS model.

Finding the cause of the reversed simulation time-step behaviour for both cases was not part of this study, and can only be speculated upon at this time. However, a solution external to Flownex was found and is discussed in Section 4.2.3. What can be said about this behaviour is that the unstable signals look like noise, maybe originating from the Flownex Nuclear solvers when reducing the simulation time step. It seems as if smaller time steps allow more natural and numerical dispersion effects to influence the simulation. Larger time steps tend to smooth out the small scale features and allow easier resolution between split models.

A further observation that can be made when comparing these two simulation time-step studies is that the coupled system is a lot more constrained when pressure is solved during the transient. By examining Figure 11, it can also be seen that the coupled system settles at a different mass flow than the reference value, and is noticeable in the fifth figure of the number. This issue will be further addressed in Section 4.2.5. In contrast, the equilibrium mass flows for the fixed pressure case (Figure 9) only show differences in the seventh figure of the number.

4.2.3 External Coupling with Filtering

As mentioned in Section 3.3.2.1, one or more intervals can be defined per simulation time step. This feature was used to implement filters for all coupling signals as shown in Figure 12. The dependent models were configured to run in the same interval with the filter application in a consecutive interval (Table 9). In this way, the coupling outputs could be filtered before being passed to the dependent models. The effect of filtering may not change results, and attention was given to that in this research. As discussed in Section 3.5.2, the filter gain and damping were chosen at 1 to have a minimum impact on the closed-loop behaviour. An optimum setting for the filter factor was found by trial and error and seen to be simulation time step dependent.

An optional Simulink logics model was added to the schedule. Its use is discussed in Section 4.2.5.

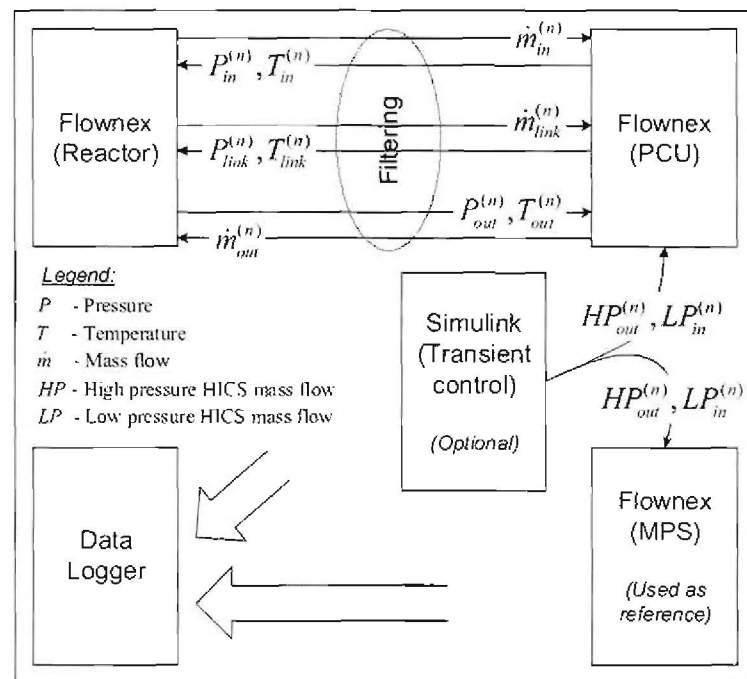


Figure 12: Flownex Nuclear External Coupling Scenario with Filtering

Table 9: Schedule Configuration for the Simulation Scenario of Figure 12

Slot	Simulation Time Step		
	Interval 1 (Optional)	Interval 2	Interval 3
1	Simulink logics model	Reference MPS model	Monitoring and filtering model
2		Reactor model	
3		PCU model	
4		Scheduler model	

The application of filtering to fixed pressure and solved pressure transients corrected the reversed time-step behaviour observed in Section 4.2.2. This is discussed below.

4.2.4 Fixed Pressure Transient

A pressure transient was executed where the system pressure was reduced at two different increasing rates for 10 s intervals starting from 10 s and 30 s, and then reversed starting from 50 s and 70 s. The stable 500 ms steady equilibrium transient state case (Figure 13) without filtering was compared with a filtered 100 ms case (Figure 14) with a filter factor of 10. As can be seen, the results were not negatively influenced by the presence of the filters, but brought stability to the coupled solution without any visible noise. (Signals used and their meanings are shown in Table 10.) Reactor inlet and outlet mass flow and pressure drop were chosen to illustrate the influence of the filters.

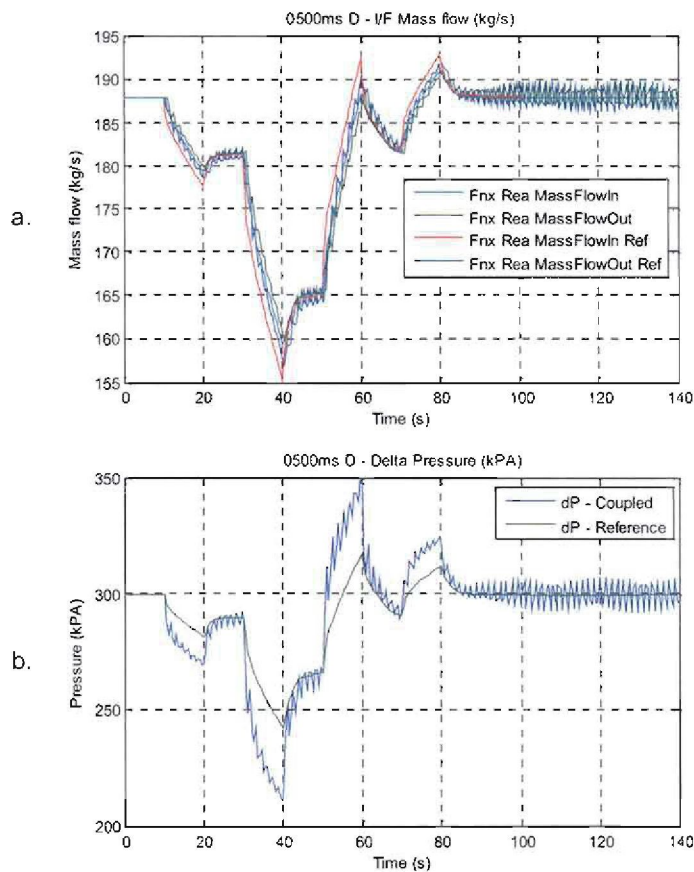


Figure 13: External Coupling without Filtering (500 ms)

Previously, a stable steady equilibrium transient state could only be achieved with a 500 ms simulation time step or larger. With the introduction of filtering of coupling signals, a 100 ms simulation time step was feasible. It was important to prove the concept and studies were also done for simulation time steps of 500 ms and 250 ms with filter factors of 1, 3 and 5 (not shown). However, it was found that if the filter factor was too large for the simulation time

step, it would unduly affect the coupled system time response. For example, a filter factor of 10 was acceptable for the 100 ms case, but not for the 500 ms case. Studies with lower simulation time steps than 100 ms were not done, but are not foreseen to be problematic.

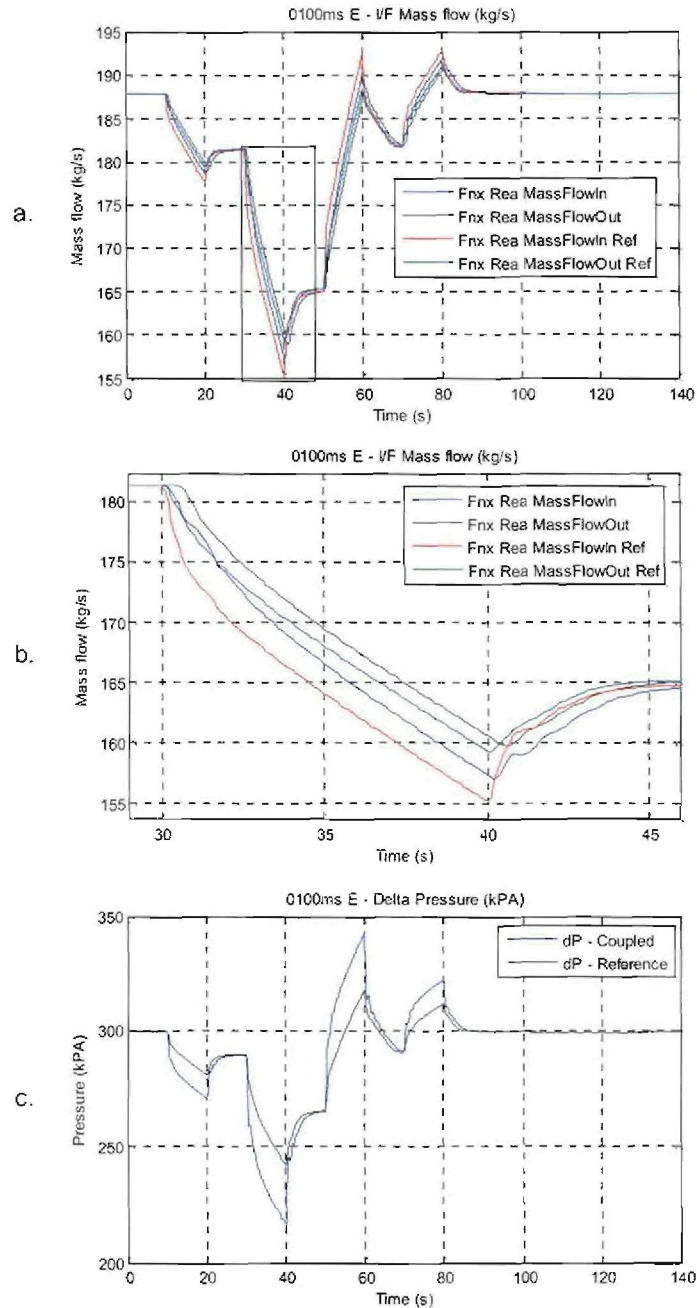


Figure 14: External Coupling with Filtering (100 ms)

The time-dependent compressible mass flow effect can be clearly seen when analysing the amplified region of Figure 14 (a) in Figure 14 (b). The coupled system has a similar response to the reference system. The difference in mass flow is proportional to the error in pressure (Figure 14 (c)). The effective time delay can be seen when analysing Figure 14 (b) at 40 s when the pressure gradient suddenly changed to zero. It is a couple of simulation time steps.

Table 10: Signal Descriptions for Figure 13 and Figure 14

Signal Name	Description
Fnx Rea MassFlowOut	Reactor outlet mass flow, calculated by the PCU model.
Fnx Rea MassFlowIn	Reactor inlet mass flow, calculated by the reactor model.
Fnx Rea MassFlowOut Ref	Reactor outlet mass flow, calculated by the reference MPS model.
Fnx Rea MassFlowIn Ref	Reactor inlet mass flow, calculated by the reference MPS model.
dP Coupled	Reactor pressure drop for the coupled solution.
dP Reference	Reactor pressure drop for the reference MPS solution.

4.2.5 Solved Pressure Transient

To investigate the solved pressure transient, a simulation time of 100 ms and filtered coupling signals were chosen to produce a stable steady equilibrium transient state. A small load-following simulation scenario was executed where the helium inventory was reduced, kept constant and then increased again (Figure 15 and Figure 16). (Signals used and their meanings are shown in Table 11.) This was done by specifying a mass flow rate into and out of the PCU at the PCU/HICS interface with the optional Simulink logics model. In this case, the pressure in the coupled system is determined by the system mass flow rate.

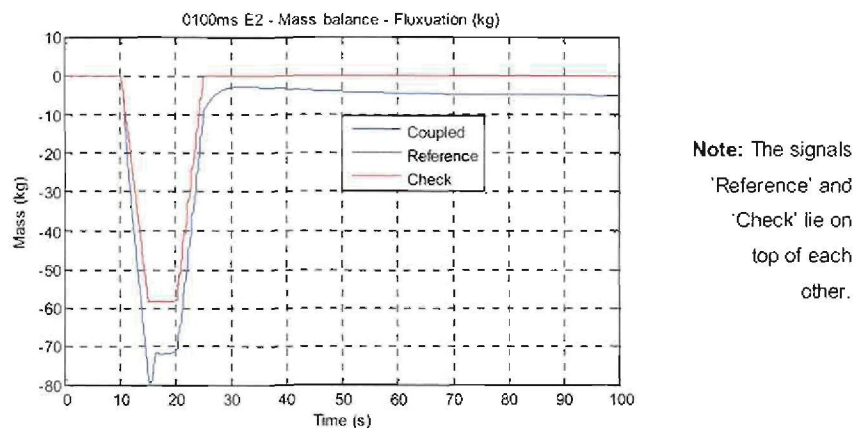


Figure 15: Solved Pressure Transient – 100 ms with Filtering

Analysing Figure 15 and Figure 16, it can be seen that conservation of mass is not maintained, and that this has adverse effects on other thermal-fluid parameters such as pressure. Clearly, these results are not acceptable.

A concept solution was postulated whereby a correction algorithm could be implemented to maintain the mass balance at the theoretically calculated level. A simple feedback correction loop was implemented where a portion of the mass balance error was either added or subtracted at the PCU/HICS interface.

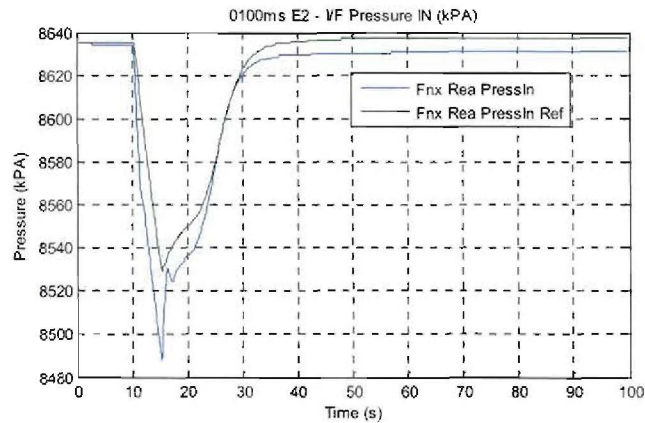


Figure 16: Solved Pressure Transient – 100 ms with Filtering (Continued)

The result of the mass balance correction is shown in Figure 17. By comparing the mass balance (Figure 17 (a)) and pressure (Figure 17 (b)), it can be seen that it is possible to correct for the mass balance error. However, a more fundamental approach is required, such as the semi-implicit coupling technique described in [13].

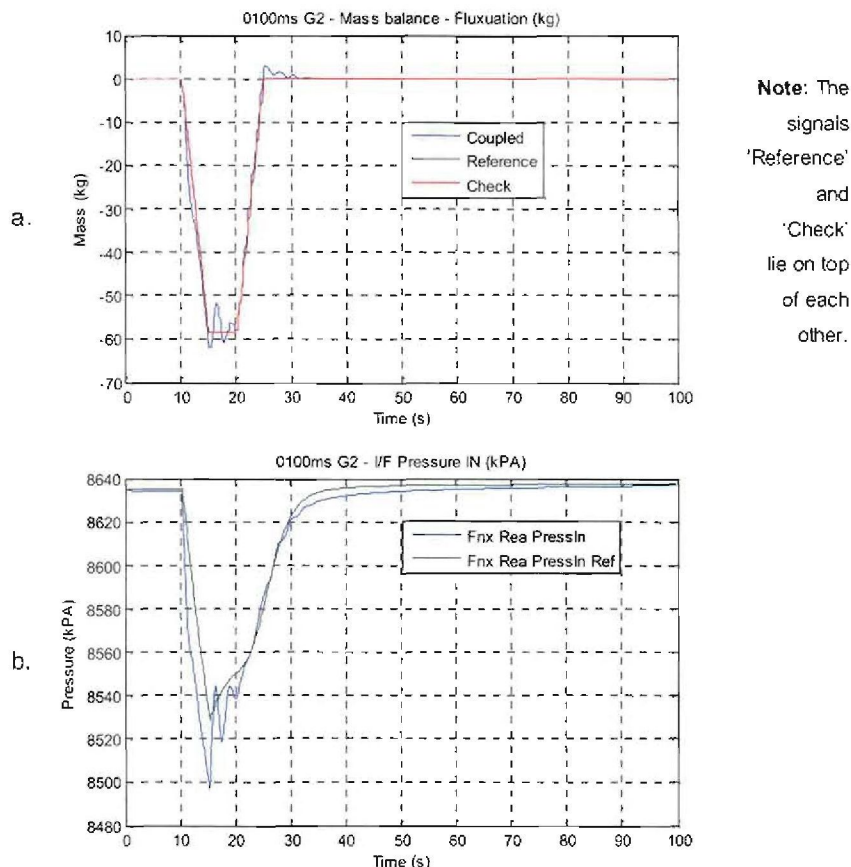


Figure 17: Solved Pressure Transient – 100 ms with Filtering and Mass Correction

Semi-implicit coupling [13] introduces a coupling boundary volume at each pair of coupling nodes/interfaces. New-time velocities at the interface depend on new-time pressures on each side of the interface and are treated in a consistent manner. The same quantities are

also transferred across the interface to conserve mass and energy. However, this research did not include determining the actual reason for the problem or finding a solution.

Table 11: Signal Descriptions for Figure 16 and Figure 17

Signal Name	Description
Coupled	Mass balance change found from adding the helium inventories calculated by the reactor and PCU models of the coupled system.
Reference	Mass balance change as calculated by the reference MPS model.
Check	Theoretically calculated mass balance change by integrating the mass flow out of and into the PCU.
Fnx Rea Press In	Reactor inlet pressure, calculated by the PCU model.
Fnx Rea Press In Ref	Reactor inlet pressure, calculated by the reference MPS model.

4.3 EXTERNAL COUPLING OF TINTE AND SIMULINK

With the external coupling of TINTE and Simulink, there are no circular thermal-fluid dependencies between the two models (refer to Section 1.1). TINTE requires six thermal-fluid boundary conditions as well as control rod position to solved. The thermal-fluid boundary conditions are inlet mass flow and temperature for the reactor and core barrel cooling channel, as well as outlet pressure for both. TINTE is started from a restart file and these initial values are already part of the restart file. However, these initial boundary values must be set up as part of the TINTE model configuration in the NEA Simulator, which will be used by the TINTE translator as reference values.

During runtime, these values can be kept constant or changed by the Simulink model. Generally, the operational control algorithm will change the control rod position with circular dependency effects to its monitored variables. However, a lookup table will generally be used to introduce predetermined thermal-fluid boundary conditions. Because these values are fixed with time, no circular thermal-fluid dependency effects can be simulated. A Flownex Nuclear MPS model transient would be run in isolation beforehand to determine the time-dependent thermal-fluid boundary conditions.

4.4 EXTERNAL COUPLING OF TINTE AND FLOWNEX NUCLEAR

Due to mass conservation not being upheld with the solved pressure transient and external coupling of Flownex Nuclear, only a fixed pressure transient was attempted for the TINTE/Flownex Nuclear coupling.

4.4.1 Coupling Methodology

The coupling methodology for the TINTE/Flownex Nuclear PCU configuration is shown in Figure 18. A reference closed-loop MPS model is used and broken at the reactor so that the interfacing nodes can resemble the TINTE model entry and exit points as closely as possible. The PCU model has three interface nodes to the reactor model: the reactor inlet, reactor outlet and a pressure equalizer link line between the reactor and PCU. However, the TINTE model does not include the link line. Therefore the link line in the PCU model was given zero flow conditions. The core barrel cooling channel in TINTE was also not coupled.

As discussed in Section 4.3, TINTE requires inlet mass flow and temperature and outlet pressure as thermal-fluid boundary conditions to the reactor and is indicated in Figure 18. The Flownex Nuclear PCU model is then configured with opposing boundary conditions.

TINTE does not solved time-dependent compressible gas flow, and this posed a stability problem in the coupling. The mass flow calculated by the Flownex Nuclear PCU model would be passed to TINTE during the next simulation time step. It would then be passed back to the Flownex Nuclear PCU model unaltered, after still another simulation time step. The use of TINTE calculated outlet mass flow in the Flownex Nuclear PCU model causes instabilities due to an increased time lag. One solution to this problem was to make the Flownex Nuclear PCU model not dependent on the TINTE calculated mass flow. It would then use its own calculated mass flow at the reactor inlet node as the boundary condition for the reactor outlet node.

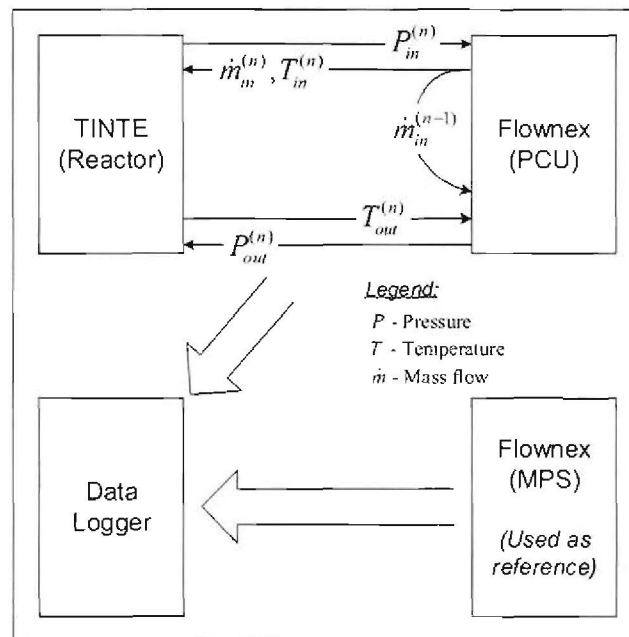


Figure 18: TINTE and Flownex Nuclear External Coupling Scenario

Reactor model alignment between TINTE and the reference Flownex Nuclear MPS model was found to be very important to produce a steady equilibrium transient state just after initialization. Offline steady-state matching of power, pressures, temperatures and mass flow is required. The TINTE and Flownex Nuclear reactor models were not aligned, and required modelling changes. Outlet temperature is a result of the axial and radial power profiles in the core, and therefore differences were expected. However, pressure drop across the reactor is purely based on physical flow conditions and should be modelled accurately. The long-term solution would be to change both models to represent reality more, but that was not part of the scope of this research. To prove the concept of an external TINTE/Flownex Nuclear coupling, the easiest route was to change the Flownex Nuclear reactor model flow conditions. Given the same boundary values, resistances in the Flownex Nuclear reactor model were changed to result in the same pressure drop as calculated by TINTE. Before model alignment, the pressure drop across the reactor differed by 50 kPa, and afterwards by 0.0073 kPa. This resulted in a final reactor outlet temperature difference of 2.5855 °C. These remaining differences were then added as offsets to the Flownex Nuclear PCU model.

After model alignment, initial values for these boundary conditions are copied from a steady-state solution from the closed-loop reference MPS model. The data exchange arrows in Figure 18 originate from the node where the values are calculated, and point to the node where the boundary conditions are applied. These boundary conditions will then be updated once the time-dependent solution starts.

4.4.2 Steady-state Equilibrium Time-step Behaviour

The steady-state equilibrium time-step behaviour was investigated for a fixed pressure transient. The flow network has a reference pressure somewhere inside, and during the transient this pressure can be changed. Mass flow in the system will be the result of this pressure. The simulation time step was used as the independent variable to perform the steady-state equilibrium time-step study.

Table 12: Schedule Configuration for the Simulation Scenario of Figure 18

Slot	Simulation Time Step
	Interval 1
1	Reference MPS model
2	TINTE reactor model
3	PCU model
4	Scheduler model

This case was investigated by using the reactor/PCU combination of Figure 18, with the schedule shown in Table 12. It was configured with only one interval and all dependent models in the same interval.

The stability behaviour was as expected, with the coupling becoming more stable as the simulation time step is reduced. The mass flow calculated by the Flownex Nuclear PCU model was used as an indicator of stability and is shown in Figure 19 and Figure 20 for decreasing simulation time steps. (Signals used and their meanings are shown in Table 13.)

After the time-dependent solution starts, a steady equilibrium transient state is achieved when the reactor inlet and outlet mass flows are equal and stable. As can be seen, the coupled system's stability improved when decreasing the simulation time step. From top to bottom, the simulation time steps were 150 ms, 120 ms, 75 ms and 50 ms.

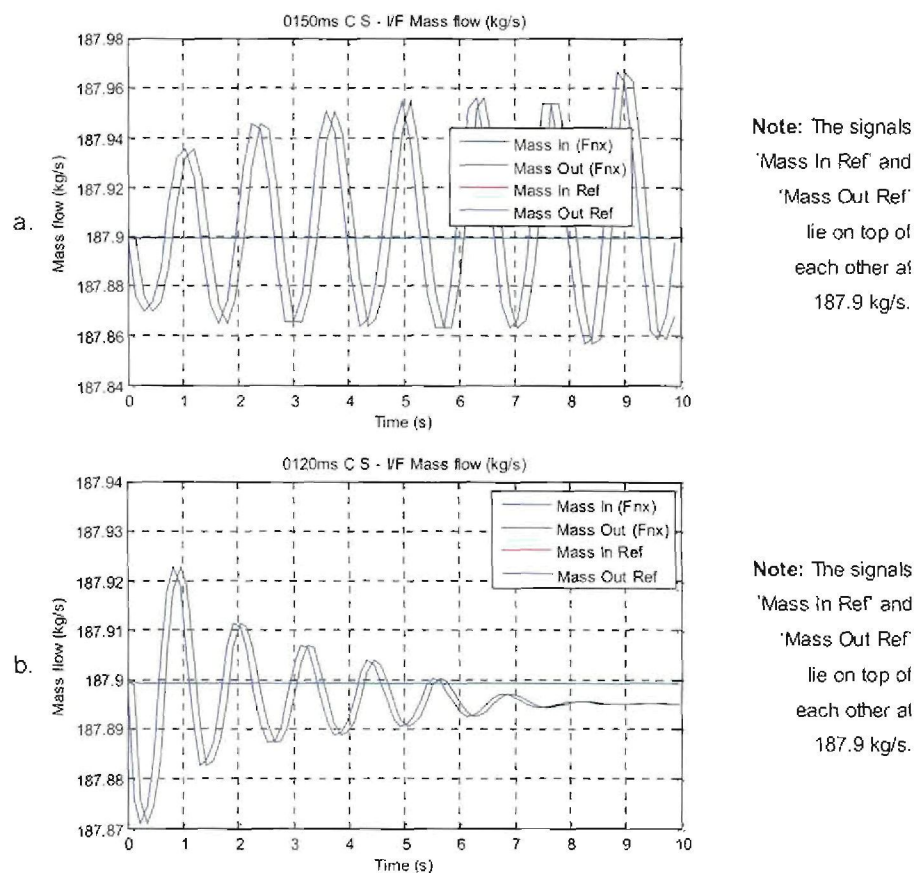


Figure 19: TINTe/Flownex Nuclear Time-step Behaviour – Fixed Pressure

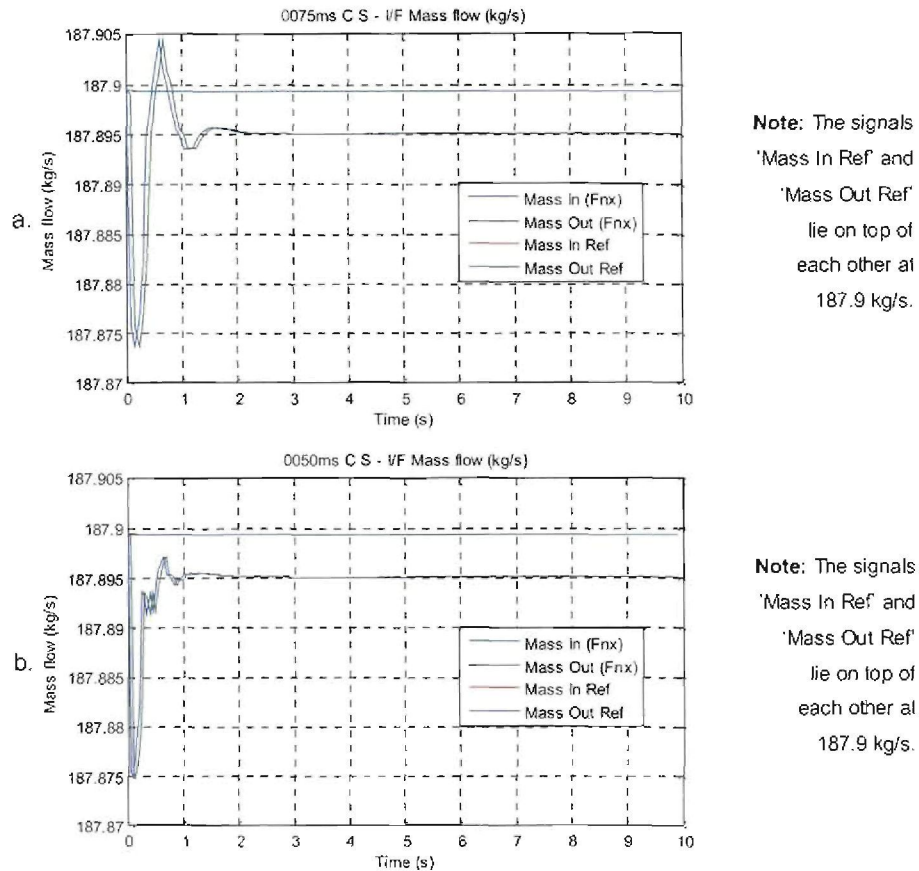


Figure 20: TINTe/Flownex Nuclear Time-step Behaviour – Fixed Pressure (Continued)

Table 13: Signal Descriptions for Figure 19 to Figure 21

Signal Name	Description
Mass In (Fnx)	Reactor inlet mass flow, calculated by the PCU model.
Mass Out (Fnx)	Reactor outlet mass flow, calculated by the PCU model.
Mass In Ref	Reactor inlet mass flow, calculated by the reference MPS model.
Mass Out Ref	Reactor outlet mass flow, calculated by the reference MPS model.
Power (TINTe)	Reactor total power, calculated by TINTe.

4.4.3 Fixed Pressure Transient

A pressure transient was executed where the system pressure was reduced at two different increasing rates for 10 s intervals starting from 10 s and 30 s, and then reversed starting from 50 s and 70 s (Figure 22). (Signals used and their meanings are shown in Table 13.) The stable 75 ms steady equilibrium transient state case was used, but resulted in large instabilities in the mass flow (Figure 21 (a)). It occurs where the mass flow rate of change suddenly increased. This suggests that the instabilities are simulation time-step related.

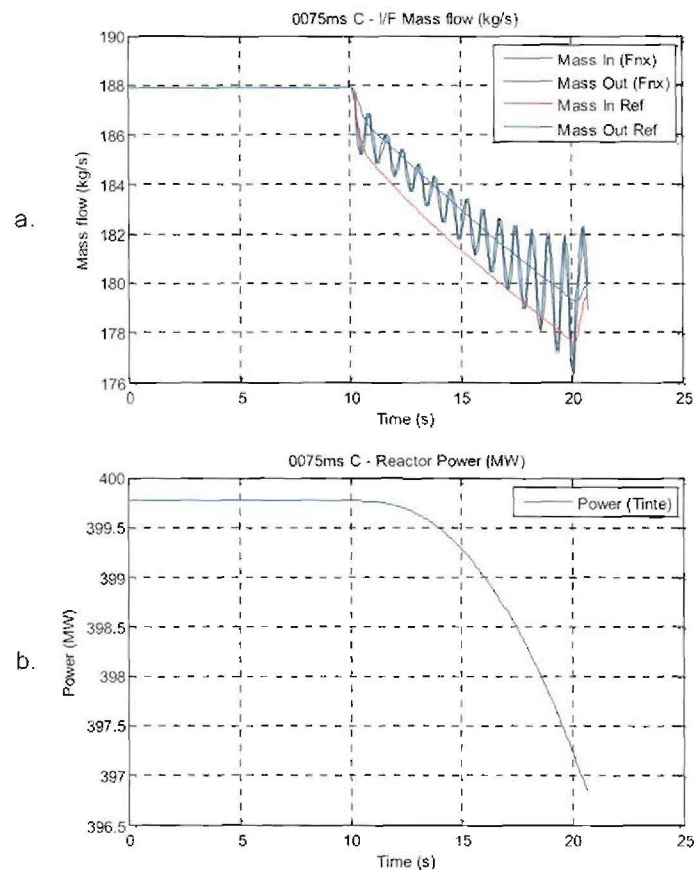


Figure 21: TINTe/Flownex Nuclear

The transient was consequently rerun with a simulation time step of 40 ms and produced the results shown in Figure 22 and Figure 23 – the coupling is now perfectly stable except for transitional effects. Note the amplified region in Figure 23 (a) of Figure 22. One can clearly see the time-dependent compressible mass flow effects calculated by the closed-loop reference solution. The coupled solution follows the reactor outlet mass flow and does not calculate time-dependent compressible mass flow effects. However, for all periods where the system pressure did not change, the coupled and reference solutions converged.

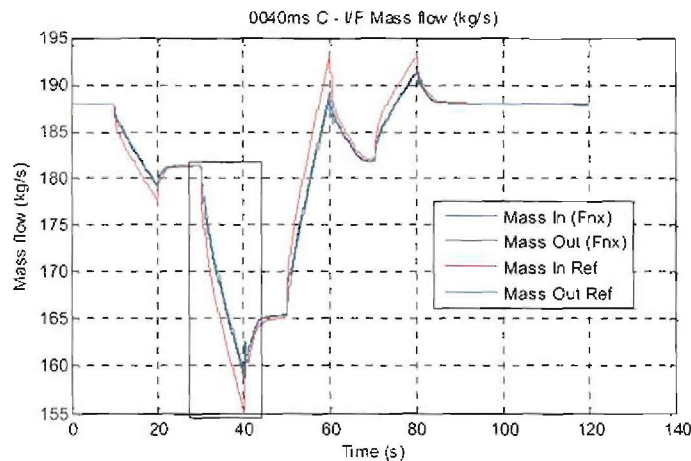


Figure 22: TINTe/Flownex Nuclear – Reduced Simulation Time Step

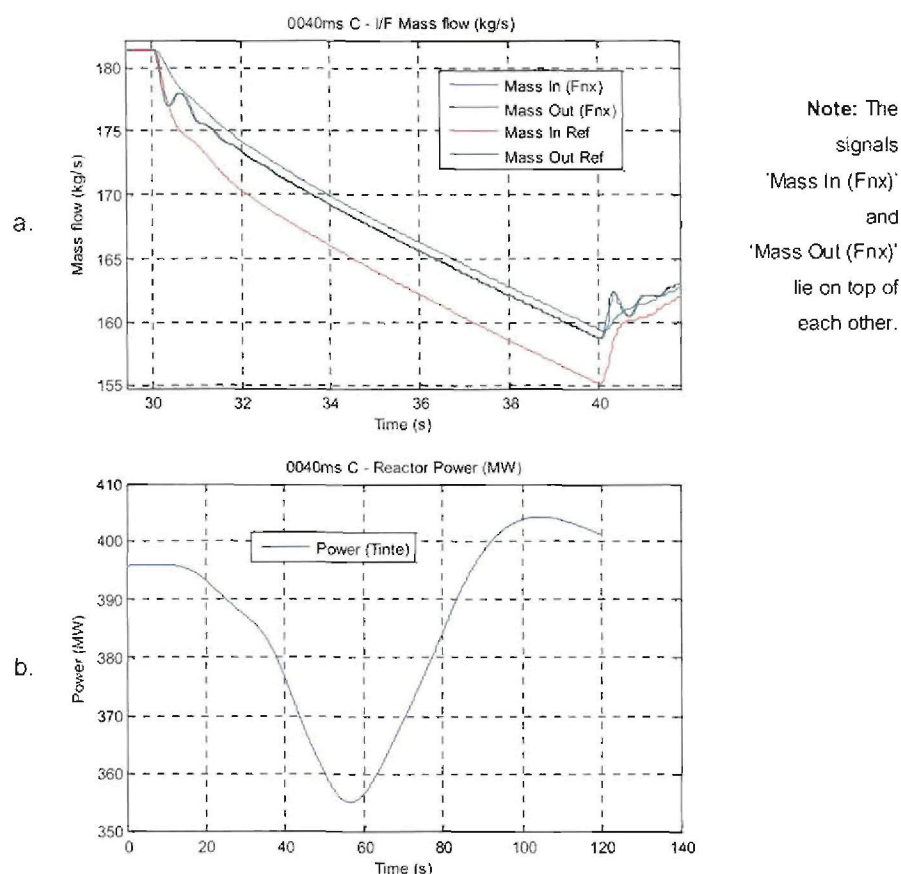


Figure 23: TINTe/Flownex Nuclear – Reduced Simulation Time Step (Continued)

4.5 PARALLEL COUPLING OF TINTe AND FLOWNEX NUCLEAR

The parallel methodology was chosen to circumvent stability problems as experienced with the other types of couplings. In this type of coupling, the basic conservation of mass and energy is being upheld due to the fact that the closed-loop Flownex Nuclear MPS model is maintained. Either solved or fixed pressure transients can therefore be attempted.

4.5.1 Methodology

The coupling methodology for the Parallel TINTe/Flownex Nuclear PCU configuration is shown in Figure 24. The complete closed-loop Flownex Nuclear MPS model, with neutronics switched off, is integrated to TINTe. The Flownex Nuclear MPS model provides the required boundary conditions to TINTe, and TINTe provides total reactor power and reactor outlet temperature to the Flownex Nuclear MPS model. The reactor thermal fluids are therefore calculated by both the Flownex Nuclear MPS model and TINTe in parallel. Transient control will be affected by control rod movement and helium extraction and injection.

A reference Flownex Nuclear MPS model also runs in parallel, but with the only inputs being the transient control via control rod movement and helium extraction and injection. As an

added benefit, the effect of simplified versus detailed time-dependent neutronics included in the closed-loop MPS can be illustrated for various transients. The advanced Flownex Nuclear reactor model included in the MPS model calculates the simplified time-dependent neutronics versus the detailed time-dependent neutronics calculated by TINTE.

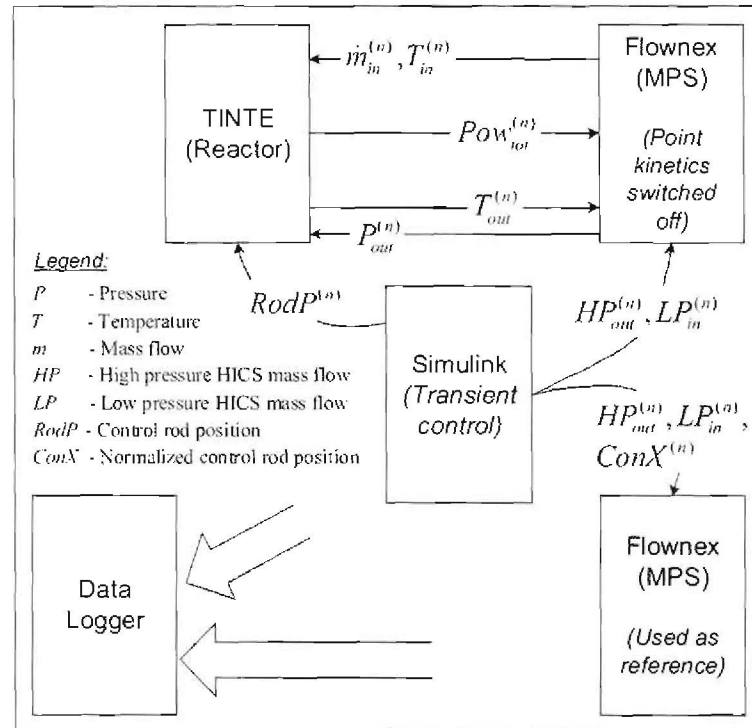


Figure 24: TINTE and Flownex Nuclear Parallel Coupling Scenario

Table 9 shows the schedule used. To enable fixed as well as variable simulation time steps, the scheduler model must be configured alone in the first interval. The logics model is in the second interval with all other dependent models in the third interval. Lastly, the data logger is configured in the last interval.

Table 14: Schedule Configuration for the Simulation Scenario of Figure 24

Slot	Simulation Time Step			
	Interval 1	Interval 2	Interval 3	Interval 4
1	Scheduler model	Simulink logics model	Reference MPS model	Monitoring and filtering model
2			MPS model	
3			TINTE model	

Once again, reactor model alignment proved to be important in terms of steady state matching of power, inlet and outlet pressures, inlet and outlet temperatures, and mass flow. Only the resulting reactor outlet temperature offset difference is important, and must be taken

into account in the coupled Flownex Nuclear MPS model. Any difference in reactor outlet temperature not taken into account will drive the closed-loop MPS to a different operating pressure.

4.5.2 Modelling Choices

The Flownex Nuclear reactor model's axial power profile was configured from a reference 3D neutronics code for steady-state, full-power operation. It is also fixed and has no radial power distribution, and cannot change with reactor state changes, such as when the control rods are inserted further into the core. Due to this, the reactor outlet temperature cannot be as accurate as that calculated by TINTE. The Flownex Nuclear reactor model's point kinetics implementation also suffers from inaccurate power calculations when the reactor state is different to the reference state. For these reasons, the Flownex Nuclear reactor model's point kinetics is discarded, and TINTE-calculated total reactor power and reactor outlet temperature used instead.

The thermal-fluid calculations implemented in the Flownex Nuclear reactor model are more advanced than those calculated by TINTE. This is especially true for the pressure drop and time-dependent compressible mass flow. For this reason, inclusion of the Flownex Nuclear reactor model in the integrated simulation scenario is preferred rather than directly using these values calculated by TINTE.

4.5.3 Control Rod Depth

In a code-to-code comparison of the TINTE reactor model and VSOP [28], the control rod worth compared favourably up to a depth of 650 cm [29]. Care was taken with the control rod transients attempted in this research not to go beyond the 650 cm mark.

The reference Flownex Nuclear reactor model included in the MPS model does not recognize actual control rod position. The closest relation that the point kinetics implementation has to actual control rod position is a non-linear relationship for normalized control rod position. Comparison between the aligned TINTE and Flownex Nuclear reactor models for a full-power steady-state equilibrium core resulted in the lookup table shown in Table 15. 'Rod_Ref' and 'ConX_Ref' were the values as modelled by the Flownex Nuclear reactor model. The steady-state full-power reference values are shown in bold, and 'Rod_New' and 'ConX_New' are the aligned values for actual and normalized control rod position. 'delta_Rod %' and 'delta_ConX %' show the differences from the original values, and indicate maximum changes of 0.99% and -6.31% respectively.

Table 15: Actual vs Normalized Control Rod Position

Rod_Ref	ConX_Ref	Rod_New	ConX_New	delta_Rod %	delta_ConX %
0.0	0.0	0.0	0.0	0.0	0.0
78.5	0.037911716	77.72492101	0.040303981	0.99%	-6.31%
95.5	0.046121897	94.55706951	0.049032232	0.99%	-6.31%
150.5	0.072684246	149.0140205	0.07727069	0.99%	-6.31%
202.56	0.097826717	200.56	0.103999674	0.99%	-6.31%
245.2	0.118419782	243.3748831	0.124052966	0.74%	-4.76%
290.2	0.140152613	288.5594455	0.145216149	0.57%	-3.61%
340.2	0.164300203	338.7645148	0.168730797	0.42%	-2.70%
390.2	0.188447793	388.9695841	0.192245445	0.32%	-2.02%
440.2	0.212595383	439.1746534	0.215760093	0.23%	-1.49%
490.2	0.236742973	489.3797227	0.239274741	0.17%	-1.07%
540.2	0.260890563	539.5847921	0.262789389	0.11%	-0.73%
590.2	0.285038153	589.7898614	0.286304037	0.07%	-0.44%
640.2	0.309185743	639.9949307	0.309818685	0.03%	-0.20%
650.0	0.313918671	649.8351243	0.314427556	0.03%	-0.16%
690.2	0.333333333	690.2	0.333333333	0.00%	0.00%

4.5.4 Variable Simulation Time Step

The previous coupling attempts where circular thermal-fluid dependencies existed only made use of fixed simulation time steps due to stability considerations.

An interesting feature of the parallel coupling methodology is that the coupled system's stability is not less than the individual stability of the coupled codes. For this reason, a variable simulation time-step scheme could be attempted and was proven to work well with a speed-up of 5.2 times for the case tested.

The variable simulation time-step algorithm is shown in Figure 25. It was implemented in Simulink together with the rest of the transient control logics. Control rod and mass flow rates were monitored and used to retrieve a simulation time step from previously determined lookup tables. It was limited by a user configurable upper limit with the lower limit being equal to the simulation time step that was configured in the Simulation Controller. Reset signals that pre-empted the transient logics were used to reset the variable simulation time step to the minimum. This helped to achieve smooth, time-dependent integration.

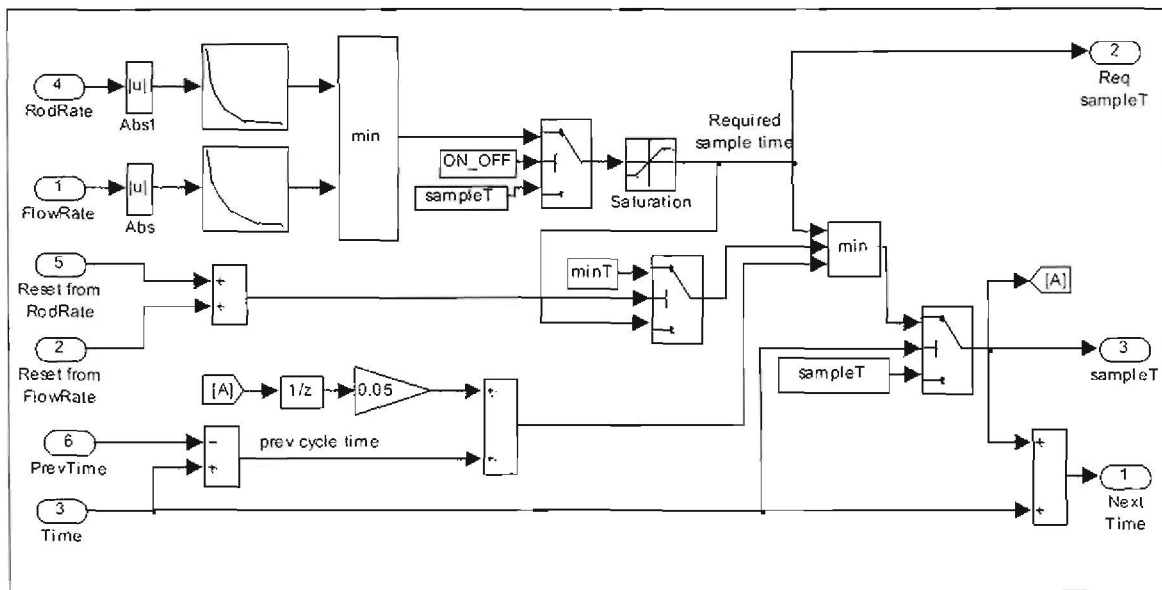


Figure 25: Variable Simulation Time-step Algorithm

4.6 CONCLUSIONS

With the progressive development of the integrated simulation, some interesting behaviour of the coupled systems has been uncovered. Contrary to what was expected, the stability of the Flownex Nuclear/Flownex Nuclear external coupling improved with larger simulation time steps. This would suggest that the coupling behaves more implicit than explicit. By introducing low-pass filtering to the coupling signals, stability at smaller time steps could be restored. The external coupling of TINTE/Flownex Nuclear proved to be fully explicit, with greater stability achieved with reduced simulation time steps. A potential drawback of the latter coupling is the fact that time-dependent compressible mass flow is not solved in the TINTE reactor model, and therefore introduces a similar limitation on the coupled solution.

For external coupled systems where circular thermal-fluid dependencies exist, the more realistic-type transients are where pressure is solved. However, coupling of two open loops is fundamentally flawed without introducing correction terms such as the semi-implicit coupling technique. To implement this successfully would require further research.

With the external coupling of TINTE and Simulink, there are no circular thermal-fluid dependencies between the two models, and the resulting closed-loop system is stable within the dynamic bounds of gain and phase margins.

The parallel coupling of TINTE and Flownex Nuclear proved to be the most successful. It is by far the most stable and versatile coupling analysed in this research, and enables variable simulation time steps to be used during the transient to make the solution less expensive.

A further development of the above-mentioned parallel coupling would be to split the Flownex Nuclear MPS model into the reactor and PCU in such a way that the stability characteristics of the former would be retained. The added benefit would be less expensive simulations and more flexibility to simulate all plant modes and transitions involving the reactor on a continuous basis. This would be possible if, say, the PCU model could be closed loop instead of open loop. The result would be a parallel coupling between TINTE and the Flownex Nuclear reactor model, and an indirect coupling between the Flownex Nuclear reactor and PCU models. In this case the PCU network will be made closed loop with a pipe that has end-to-end thermal-fluid characteristics similar to that of the Flownex Nuclear reactor model. Similar approaches to the indirect coupling performed in [8] and [9] should be performed.

5. TEST CASES

5.1 INTRODUCTION

This chapter presents complete results for selected test cases. It starts with an application of the external Flownex Nuclear/Flownex Nuclear coupling showing a fixed pressure load-follow transient. The external TINTE/Flownex Nuclear coupling follows, and a similar fixed pressure transient is presented. Solved pressure transients are not attempted for these due to the conservation laws not being upheld for the external couplings investigated.

Of the coupling methodologies investigated, the parallel TINTE/Flownex Nuclear coupling is by far the most versatile and stable. For this coupling, a solved pressure transient is simulated with combined load follow, followed by control rod withdrawal and insertion. As a bonus, results illustrating the application of variable simulation time steps are presented.

5.2 FLOWNEX NUCLEAR/FLOWNEX NUCLEAR – FIXED PRESSURE TRANSIENT

Two fixed pressure transient cases will be presented for this coupling: one without and one with filtering of the coupling signals.

5.2.1 Load Follow with No Filtering

A fixed pressure transient was executed with the coupled system shown in Figure 6. The simulation time of 1 000 ms was chosen to produce a known stable steady equilibrium transient state. A load-following scenario to approximately 40% of the mass flow at full power was simulated by changing the system pressure in two consecutive reducing and increasing intervals (Figure 26 to Figure 29). (Signals used and their meanings are shown in Table 16.) The scale at which the results are presented shows a near-perfect match to the reference solution.

In the real plant, the maximum mass flow rate of change is limited to approximately 12 kg/s due to PCU constraints. This will result in a power reduction from 100% to 40% in approximately 400 s, whereas the transient shown here resulted in a similar power reduction in approximately 100 s. The reason behind the quick inventory change presented here was to try and excite plant dynamics to determine if the 1 000 ms simulation time step was adequate to produce a stable simulation.

Figure 26 (a) shows the reactor inlet and outlet pressures, which is a direct result of the pressure transient. The pressure drop is shown in Figure 26 (b). The coupled system introduces differences during the transient but, during the steady periods, the pressure returns to the reference values.

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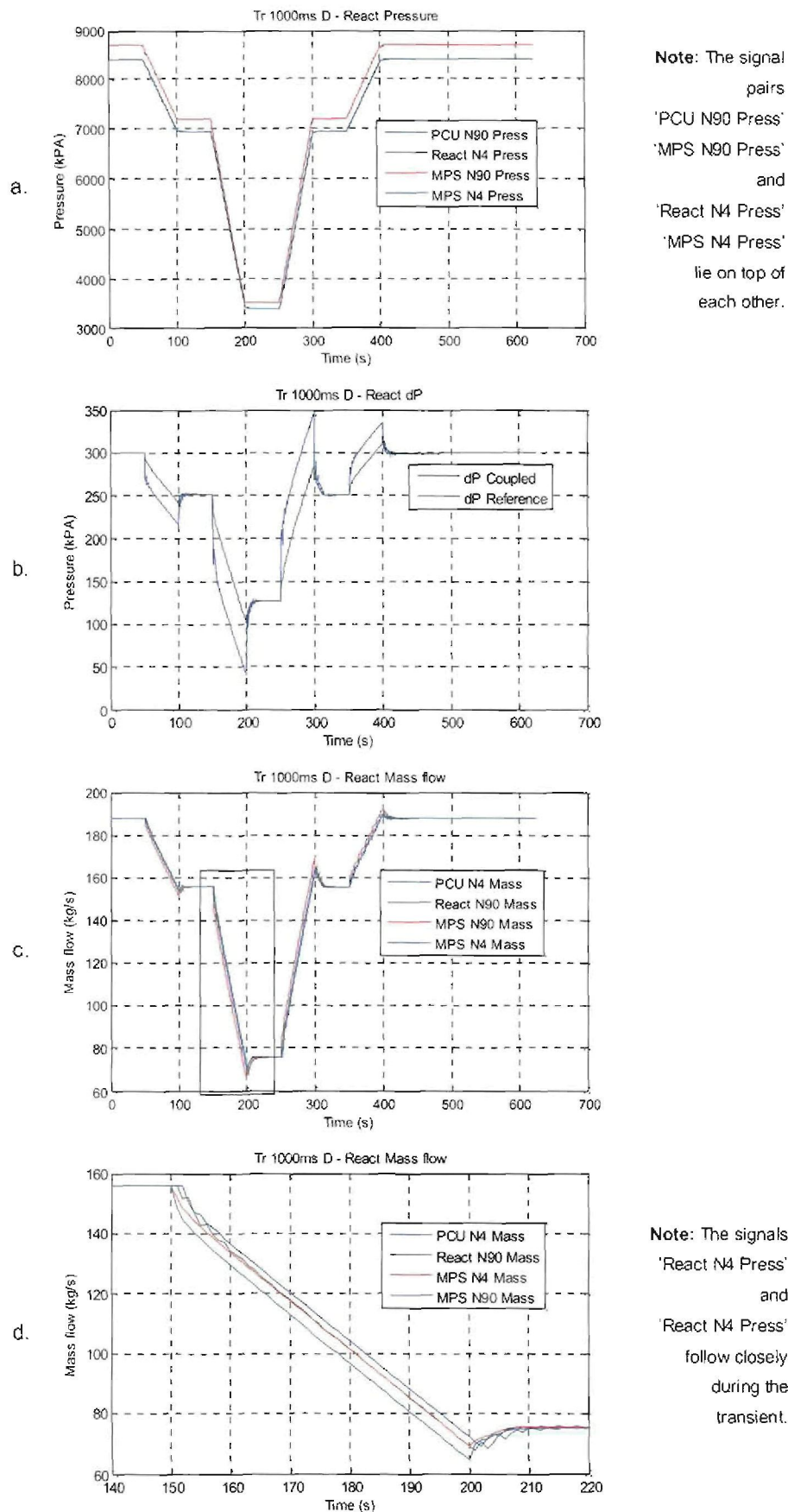


Figure 26: Fixed Pressure Transient – 1 000 ms without Filtering

The reactor inlet and outlet mass flow (Figure 26 (c)) is a good, but not perfect, fit to the reference values. Note the delayed mass flow of the coupled system in Figure 26 (d) (amplified region of Figure 26 (c)) during the transient due to the error in pressure drop. Some oscillations can also be seen in the transitional regions. During periods of steady mass flow, the coupled and reference system solutions converge.

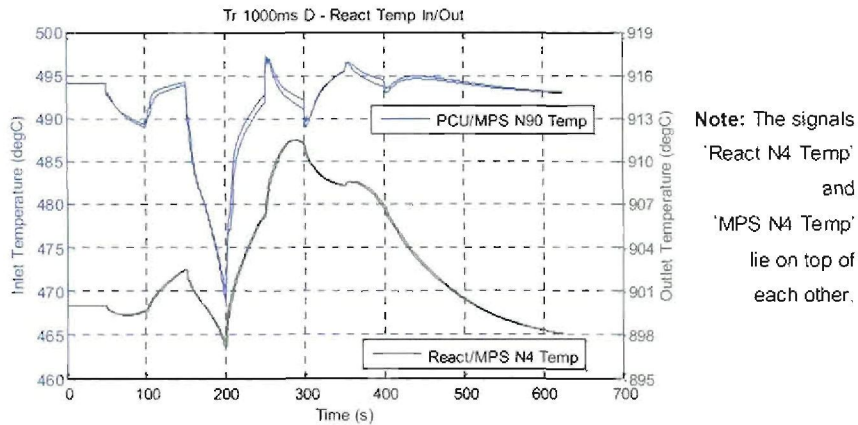


Figure 27: Fixed Pressure Transient – 1 000 ms without Filtering (Continued)

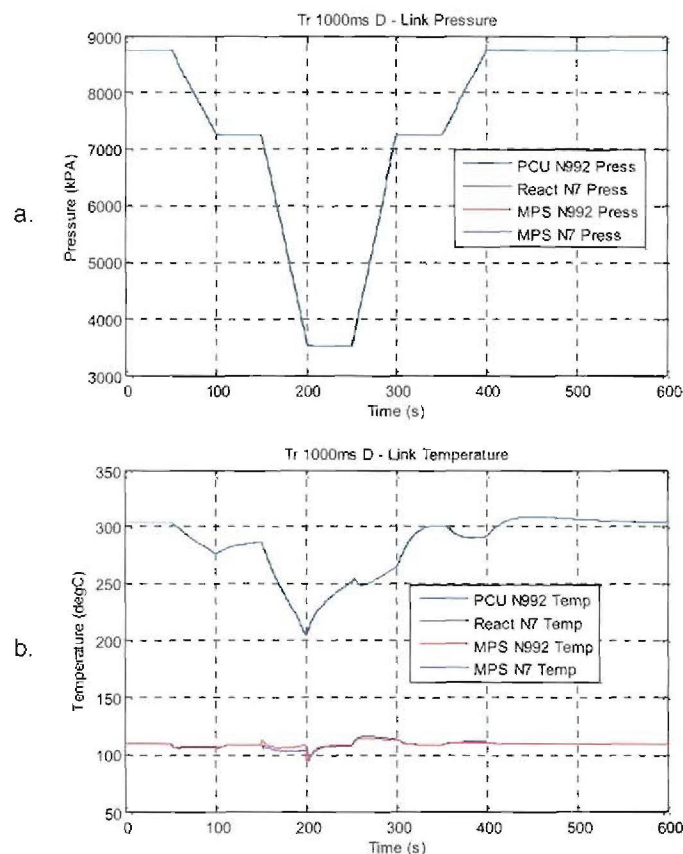
The reactor inlet and outlet temperatures (Figure 27) follow the reference values closely, although the inlet temperature is slightly more affected by the external coupling.

Table 16: Signal Descriptions for Figure 26 to Figure 29

Signal Name	Description
PCU N90 Press	Reactor inlet pressure, calculated by the PCU model.
React N4 Press	Reactor outlet pressure, calculated by the reactor model.
MPS N90 Press	Reactor inlet pressure, calculated by the reference MPS model.
MPS N4 Press	Reactor outlet pressure, calculated by the reference MPS model.
dP Coupled	Reactor pressure drop for the coupled solution.
dP Reference	Reactor pressure drop for the reference MPS solution.
React N90 Mass	Reactor inlet mass flow, calculated by the reactor model.
PCU N4 Mass	Reactor outlet mass flow, calculated by the PCU model.
MPS N90 Mass	Reactor inlet mass flow, calculated by the reference MPS model.
MPS N4 Mass	Reactor outlet mass flow, calculated by the reference MPS model.
PCU N90 Temp	Reactor inlet temperature, calculated by the PCU model.
React N4 Temp	Reactor outlet temperature, calculated by the reactor model.
MPS N90 Temp	Reactor inlet temperature, calculated by the reference MPS model.
MPS N4 Temp	Reactor outlet temperature, calculated by the reference MPS model.

Signal Name	Description
PCU N992 Press	Link line pressure on the PCU side, calculated by the PCU model.
React N7 Press	Link line pressure on the reactor side, calculated by the reactor model.
MPS N992 Press	Link line pressure on the PCU side, calculated by the reference MPS model.
MPS N7 Press	Link line pressure on the reactor side, calculated by the reference MPS model.
PCU N992 Temp	Link line temperature on the PCU side, calculated by the PCU model.
React N7 Temp	Link line temperature on the reactor side, calculated by the reactor model.
MPS N992 Temp	Link line temperature on the PCU side, calculated by the reference MPS model.
MPS N7 Temp	Link line temperature on the reactor side, calculated by the reference MPS model.
PCU 990 Mass	Link line mass flow, calculated by the PCU model.
React 990 Mass	Link line mass flow, calculated by the reactor model.
MPS 990 Mass	Link line mass flow, calculated by the reference MPS model.

The link line pressures (Figure 28 (a)) are also a direct result of the pressure transient with very few differences, as expected. The link line temperatures (Figure 28 (b)) are well matched with slightly more differences visible for the temperature on the PCU side. The link line mass flow (Figure 29 (a)) shows good resemblance to the reference values.



Note: All signals
lie on top
of each other.

Note: The
signals pairs
'PCU N992 Temp'
'MPS N992 Temp'
and
'React N7 Temp'
'MPS N7 Temp'
follow closely
during the
transient

Figure 28: Fixed Pressure Transient – 1 000 ms without Filtering (Continued)

Note the similar but less damped behaviour of the mass flow to the reference solution (Figure 29 (b)) where Figure 29 (a) has been amplified.

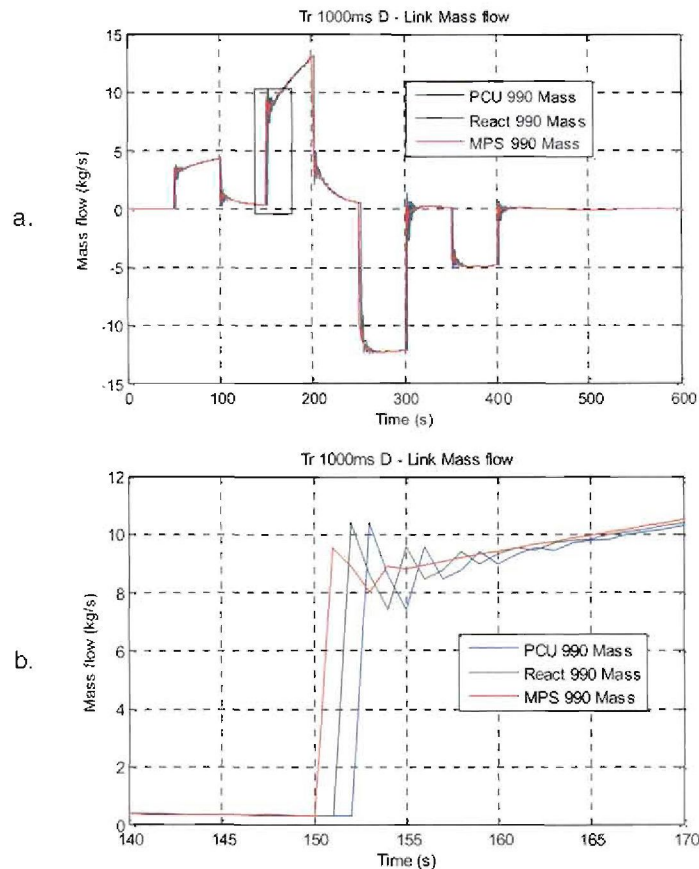


Figure 29: Fixed Pressure Transient – 1 000 ms without Filtering (Continued)

5.2.2 Load Follow with Filtering

A fixed pressure transient was executed with the coupled system shown in Figure 12 with filtering of the coupling signals. The same 100 ms case as presented in Section 4.2.4 was repeated here. System pressure was reduced at two different increasing rates for 10 s intervals starting from 10 s and 30 s, and then reversed starting from 50 s and 70 s (Figure 30 to Figure 33). (Signals used and their meanings are shown in Table 17.)

Note that the timescale of this transient compared to that in Section 5.2.1 is amplified six times. In this case the simulation time step is ten times smaller, and therefore the effective delay introduced by the coupling would also be an order of magnitude less. It is also expected that more of the faster dynamics can be captured with the smaller simulation time step.

Figure 30 (a) and Figure 30 (b) show the reactor inlet and outlet pressures respectively, with the pressure drop shown in Figure 30 (c). The coupled system introduces differences during the transient but, during the steady periods, the pressure returns to the reference values.

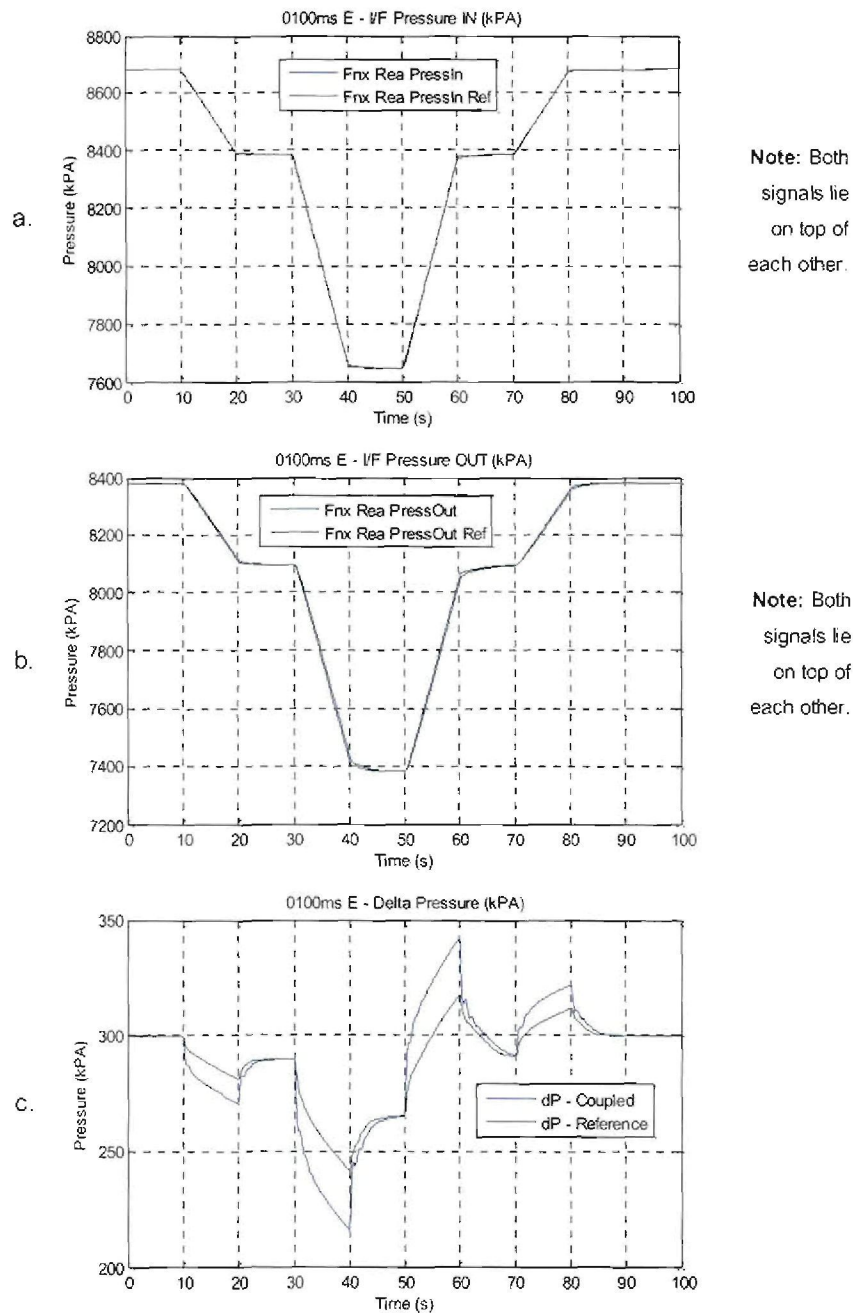


Figure 30: Fixed Pressure Transient – 100 ms with Filtering

Table 17: Signal Descriptions for Figure 30 to Figure 33

Signal Name	Description
Fnx Rea PressOut	Reactor outlet pressure, calculated by the reactor model.
Fnx Rea PressIn	Reactor inlet pressure, calculated by the PCU model.
Fnx Rea PressOut Ref	Reactor outlet pressure, calculated by the reference MPS model.
Fnx Rea PressIn Ref	Reactor inlet pressure, calculated by the reference MPS model.
dP Coupled	Reactor pressure drop for the coupled solution.

Signal Name	Description
dP Reference	Reactor pressure drop for the reference MPS solution.
Fnx Rea TempOut	Reactor outlet temperature, calculated by the reactor model.
Fnx Rea TempIn	Reactor inlet temperature, calculated by the PCU model.
Fnx Rea TempOut Ref	Reactor outlet temperature, calculated by the reference MPS model.
Fnx Rea TempIn Ref	Reactor inlet temperature, calculated by the reference MPS model.
Fnx Rea MassFlowOut	Reactor outlet mass flow, calculated by the PCU model.
Fnx Rea MassFlowIn	Reactor inlet mass flow, calculated by the reactor model.
Fnx Rea MassFlowOut Ref	Reactor outlet mass flow, calculated by the reference MPS model.
Fnx Rea MassFlowIn Ref	Reactor inlet mass flow, calculated by the reference MPS model.
Fnx Link MassFlow	Link line mass flow, calculated by the PCU model.
Fnx Link MassFlow Ref	Link line mass flow, calculated by the MPS model.

The inlet (Figure 31 (a)) and outlet (Figure 31 (b)) temperatures follow the reference solution closely. The effect of the delay introduced by the parallel data transfer is evident.

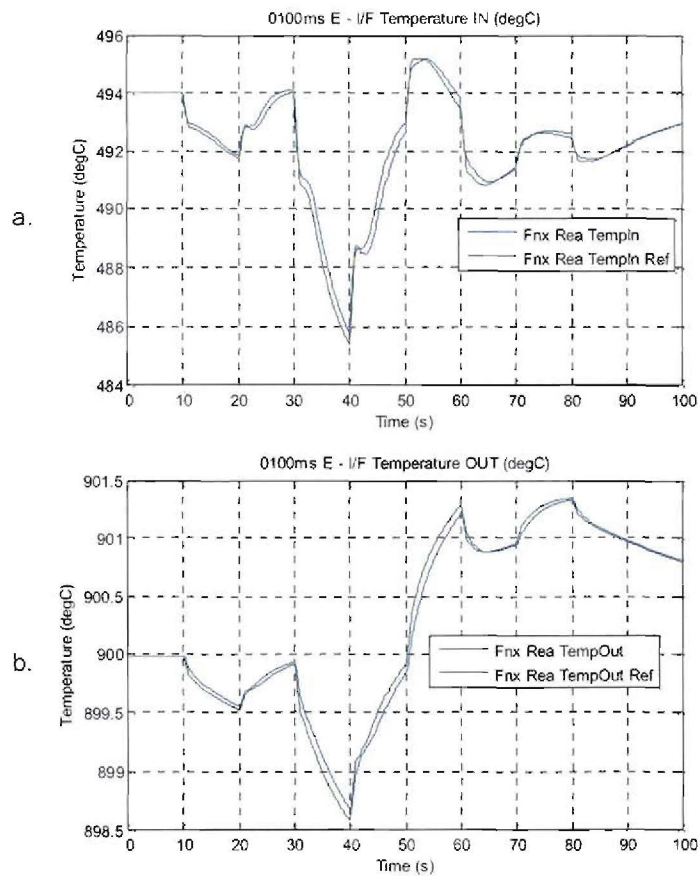


Figure 31: Fixed Pressure Transient – 100 ms with Filtering (Continued)

When examining the reactor inlet and outlet mass flow in Figure 32 (a), the effect of the difference in pressure drop observed in Figure 30 (c) can be seen here, as pressure has a direct influence on mass flow. Notice the amplified region of Figure 32 (b) in Figure 32 (a). The delayed reactor inlet and outlet mass flow can be seen clearly. Interesting to note is that although the coupled system has a delayed response, it preserves time-dependent compressible mass flow, similar to the reference system.

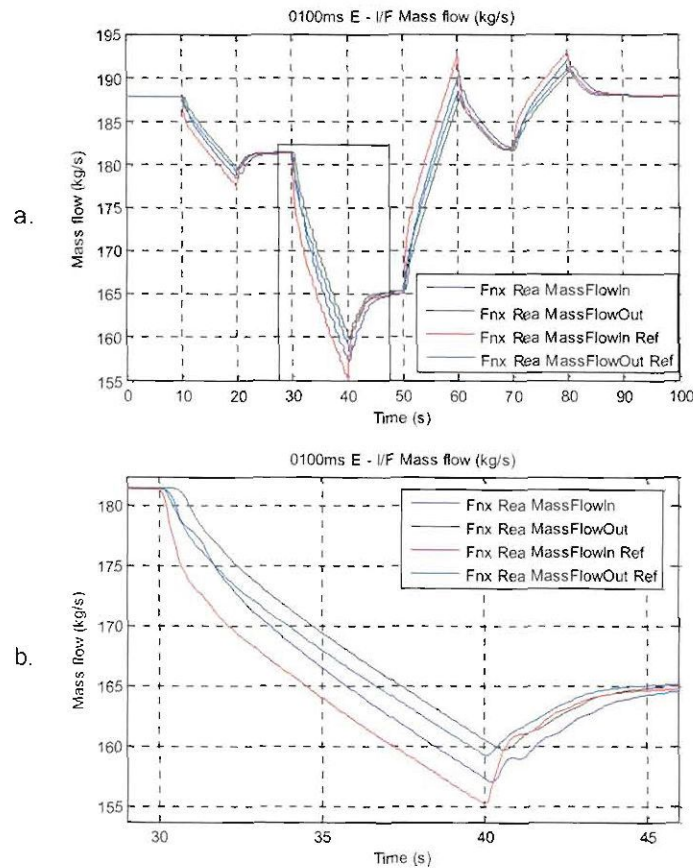


Figure 32: Fixed Pressure Transient – 100 ms with Filtering (Continued)

The link line mass flow (Figure 33 (a)) shows good resemblance to the reference values, although it is more under-damped during the transitional dynamics, as can be seen in the amplified region (Figure 33 (b)).

Also note that when comparing Figure 33 (b) with Figure 29 (b), more oscillations can be seen in the reference solution for the 100 ms case. This would suggest that a simulation time step of 1 000 ms masked these transitional dynamics. Thus, although both these cases were stable, depending on the outcome sought for the simulation, the smaller simulation time step could be required, which is made possible by introducing the filtering technique.

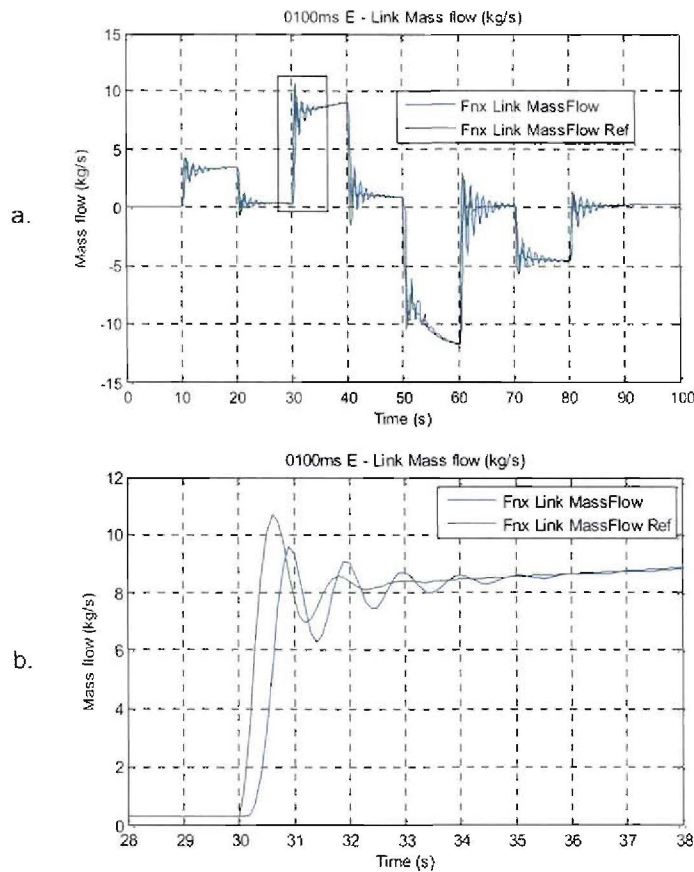


Figure 33: Fixed Pressure Transient – 100 ms with Filtering (Continued)

5.3 TINTÉ/FLOWNEX NUCLEAR – FIXED PRESSURE TRANSIENT

A fixed pressure transient was executed with the coupled system shown in Figure 18. The same 40 ms case as presented in Section 4.4.3 was repeated here. System pressure was reduced at two different increasing rates for 10 s intervals starting from 10 s and 30 s, and then reversed starting from 50 s and 70 s (Figure 34 to Figure 37). (Signals used and their meanings are shown in Table 18.)

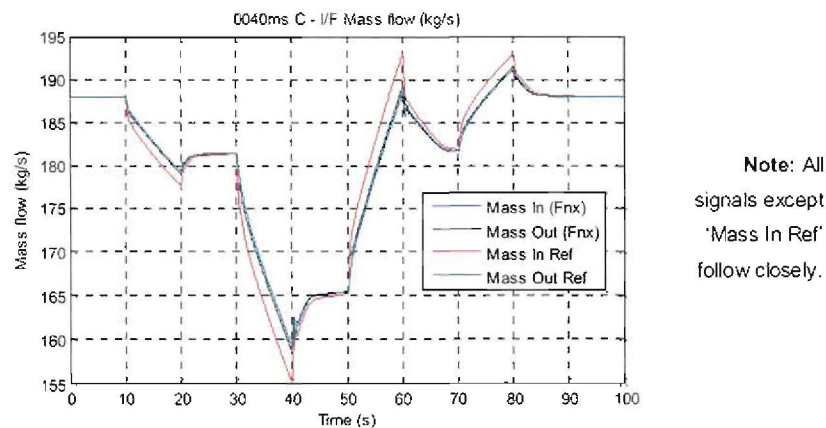


Figure 34: Fixed Pressure Transient – 40 ms

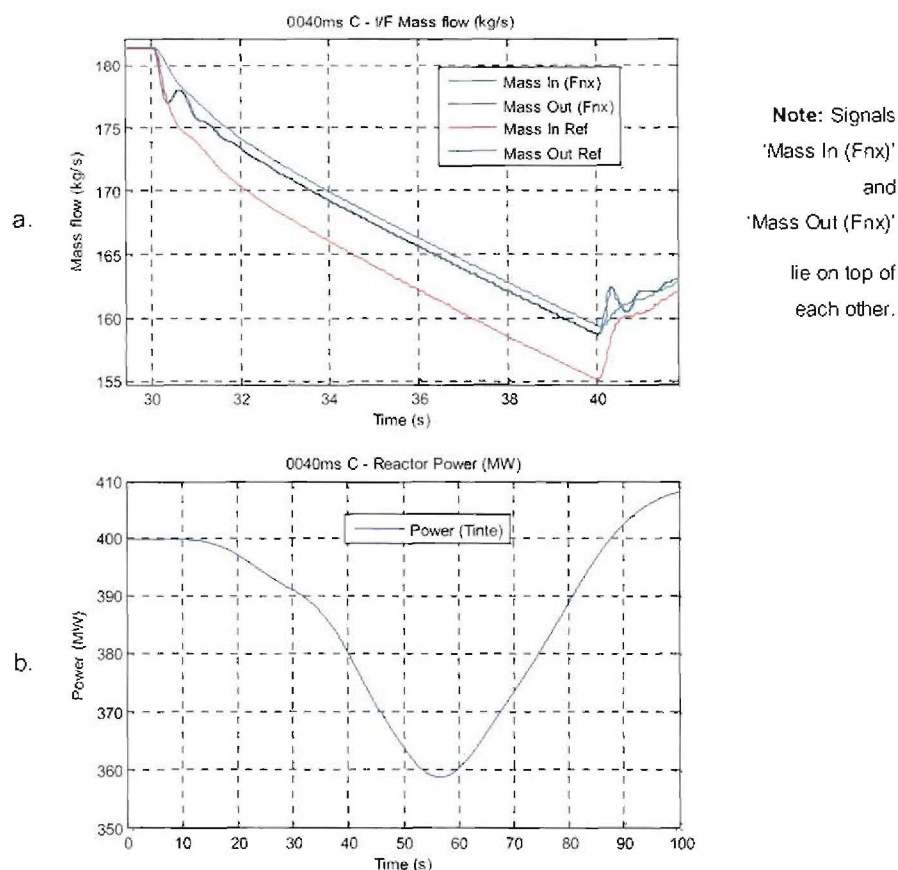


Figure 35: Fixed Pressure Transient – 40 ms (Continued)

The reactor inlet and outlet mass flow is shown in Figure 34, with an amplified region shown in Figure 35 (a). The mass flow of the coupled solution follows the reactor outlet mass flow calculated by the reference solution. Remember that for this coupling, no time-dependent compressible mass flow effects are modelled. The reactor total power as calculated by TINTE is shown in Figure 35 (b).

Table 18: Signal Descriptions for Figure 34 to Figure 37

Signal Name	Description
Press In (TINTE)	Reactor inlet pressure, calculated by TINTE.
Press Out (Fnx)	Reactor outlet pressure, calculated by the PCU model.
Press In Ref	Reactor inlet pressure, calculated by the reference MPS model.
Press Out Ref	Reactor outlet pressure, calculated by the reference MPS model.
dP Coupled	Reactor pressure drop for the coupled solution.
dP Reference	Reactor pressure drop for the reference MPS solution.
Temp Out (TINTE)	Reactor outlet temperature, calculated by TINTE.
Temp In (Fnx)	Reactor inlet temperature, calculated by the PCU model.

Signal Name	Description
Temp Out Ref	Reactor outlet temperature, calculated by the reference MPS model.
Temp In Ref	Reactor inlet temperature, calculated by the reference MPS model.
dT Coupled	Reactor temperature difference for the coupled solution.
dT Reference	Reactor temperature difference for the reference MPS solution.
Mass Out (Fnx)	Reactor outlet mass flow, as used internally by the PCU model.
Mass In (Fnx)	Reactor inlet mass flow, calculated by the PCU model.
Mass Out Ref	Reactor outlet mass flow, calculated by the reference MPS model.
Mass In Ref	Reactor inlet mass flow, calculated by the reference MPS model.
Power (TINTE)	Reactor total power, calculated by TINTE.

Reactor inlet and outlet pressures follow a similar trend as the all Flownex Nuclear coupling in the previous section, as shown in Figure 36 (a) and Figure 36 (b) respectively. Note the pressure difference in Figure 37 (a). The coupled system introduces differences during the transient, but during the steady periods, the pressure returns to the reference values. The spikes in pressure drop calculated by the coupled solution can be seen to have an effect on the outlet temperature calculated by TINTE (small blips at similar times in Figure 37 (a)).

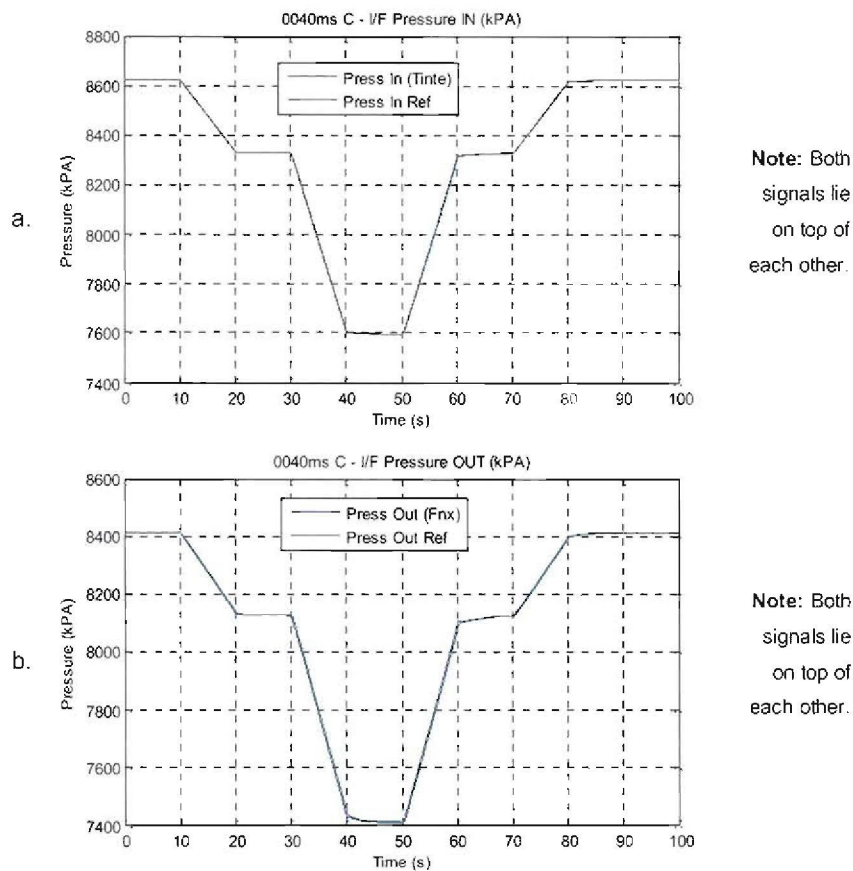


Figure 36: Fixed Pressure Transient – 40 ms (Continued)

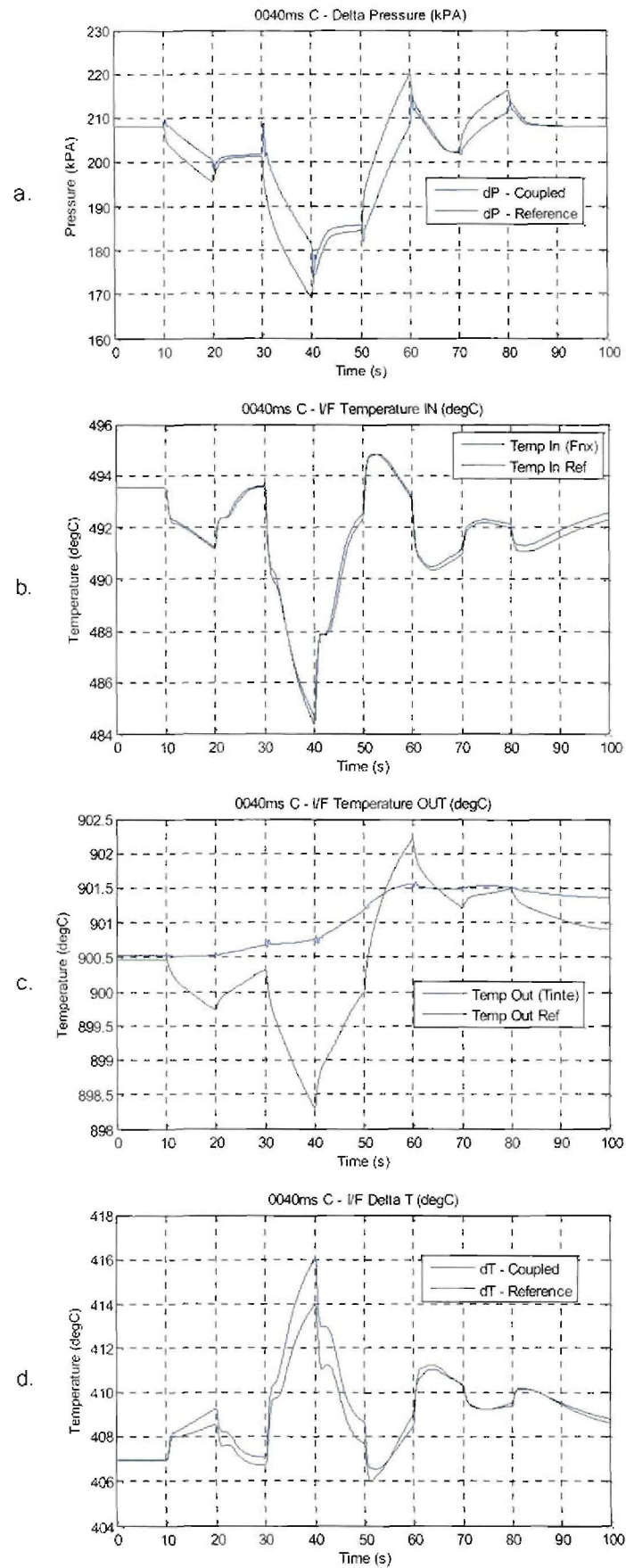


Figure 37: Fixed Pressure Transient – 40 ms (Continued)

Reactor inlet temperature shows a good correlation to the reference solution (Figure 37 (b)), but the reactor outlet temperature as calculated by TINTE is different (Figure 37 (c)). This is also highlighted by the temperature difference across the reactor (Figure 37 (d)).

The value of the TINTE/Flownex Nuclear PCU coupling can now be seen. Reactor outlet temperature is largely determined by the axial and radial power distribution in the core, which is not present in the reference solution. As a percentage of the nominal value the difference is very small, but the trend of the reference solution is totally different. This could have an effect on the operational control algorithm design for the reactor outlet temperature control.

5.4 PARALLEL TINTE/FLOWNEX NUCLEAR – SOLVED PRESSURE TRANSIENT

The results of the previous two sections are inspiring, but not of real practical use, as they are limited to fixed pressure transients. Real life transients are solved pressure transients, and the parallel coupling of TINTE and the Flownex Nuclear MPS provides this capability. Two cases are presented: one with fixed and one with variable simulation time steps.

5.4.1 Load Follow with Control Rod Withdrawal and Insert

A solved pressure transient was executed with the coupled system shown in Figure 24 for a simulation time step of 200 ms. Inventory was reduced at a constant rate of 12 kg/s to result in approximately 40% power. A steady settling down period followed, with an increase in inventory at the same rate to achieve the original full-power inventory level (Figure 38). After another steady settling down time, a control rod withdrawal to 0 cm was done at a rate of 1 cm/s. The control rods were then kept constant and consequently reinserted at the same rate to a deeper level than before (Figure 39). The complete set of results is shown in Figure 40 to Figure 44. (Signals used and their meanings are shown in Table 19.)

Please note that with this coupling methodology, the reference MPS model is compared to the coupled solution, which is taken as the benchmark.

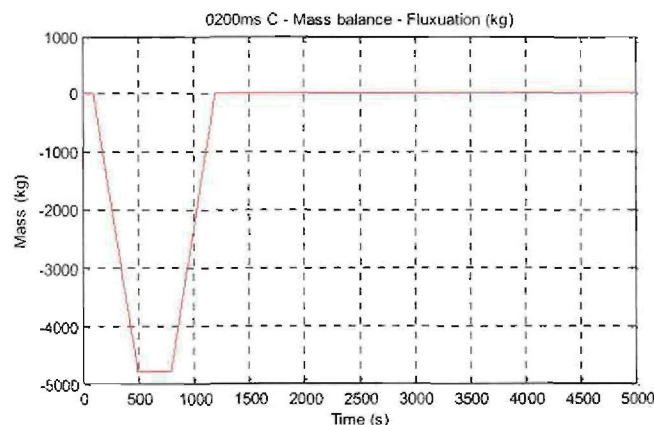


Figure 38: Solved Pressure Transient – 200 ms

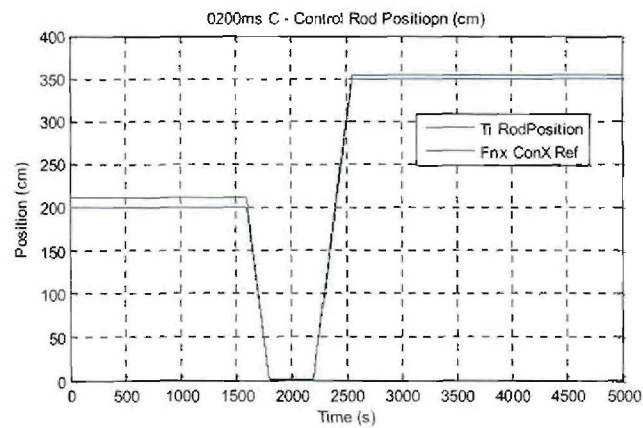


Figure 39: Solved Pressure Transient – 200 ms (Continued)

Table 19: Signal Descriptions for Figure 38 to Figure 44

Signal Name	Description
Ti RodPosition	Control rod position sent to TINTE, calculated by the Simulink model.
Fnx ConX Ref	Normalized control rod position sent to the reference MPS model, calculated by the Simulink model.
Ti PressureOut R	Reactor outlet pressure, calculated by the coupled MPS model.
Fnx Rea PressIn	Reactor inlet pressure, calculated by the coupled MPS model.
Fnx Rea PressOut Ref	Reactor outlet pressure, calculated by the reference MPS model.
Fnx Rea PressIn Ref	Reactor inlet pressure, calculated by the reference MPS model.
dP Coupled	Reactor pressure drop for the coupled solution.
dP Reference	Reactor pressure drop for the reference MPS solution.
Fnx Rea TempOut	Reactor outlet temperature, calculated by the coupled MPS model.
Ti ROT (TINTE)	Reactor outlet temperature, calculated by TINTE.
Ti GasTempIn R	Reactor inlet temperature, calculated by the coupled MPS model.
dT Coupled	Reactor temperature difference for the coupled solution.
dT Reference	Reactor temperature difference for the reference MPS solution.
Fnx Rea TempOut Ref	Reactor outlet temperature, calculated by the reference MPS model.
Fnx Rea TempIn Ref	Reactor inlet temperature, calculated by the reference MPS model.
Ti MaxFuelTemp (TINTE)	Maximum fuel temperature, calculated by TINTE.
Ti AvgFuelTemp (TINTE)	Average fuel temperature, calculated by TINTE.
Ti AvgModTemp (TINTE)	Average moderator temperature, calculated by TINTE.
Fnx Rea FuelTemp Ref	Average fuel temperature, calculated by the reference MPS model.
Fnx Rea ModTemp Ref	Average moderator temperature, calculated by the reference MPS model.

Signal Name	Description
Fnx Rea MassFlowOut	Reactor outlet mass flow, calculated by the coupled MPS model.
Ti MassFlowIn R	Reactor inlet mass flow, calculated by the coupled MPS model.
Fnx Rea MassFlowOut Ref	Reactor outlet mass flow, calculated by the reference MPS model.
Fnx Rea MassFlowIn Ref	Reactor inlet mass flow, calculated by the reference MPS model.
Fnx Link MassFlow	Link line mass flow, calculated by the coupled MPS model.
Fnx Link MassFlow Ref	Link line mass flow, calculated by the reference MPS model.
Fnx Rea TotPower	Reactor total power, as used by the coupled MPS model.
Fnx Rea TotPower Ref	Reactor total power, calculated by the reference MPS model.
Ti TotalPower (TINTE)	Reactor total power, calculated by TINTE.
Fnx ExcessPower	Shaft excess power, calculated by the coupled MPS model.
Fnx ExcessPower Ref	Shaft excess power, calculated by the reference MPS model.

The reactor inlet and outlet mass flow can be seen in Figure 40 (a). Small differences can be seen during and after the control rod transient. This is a direct result of using the coupled TINTE reactor outlet temperature. Link line mass flow is shown in Figure 40 (b).

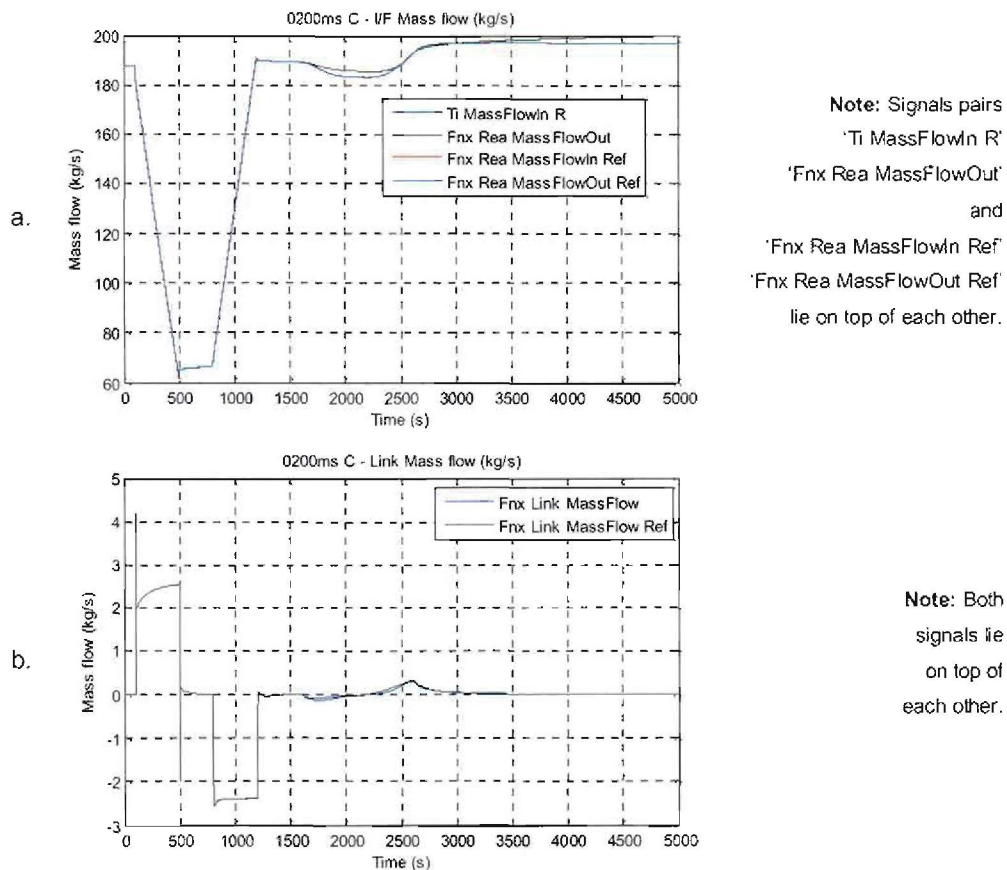


Figure 40: Solved Pressure Transient – 200 ms (Continued)

Reactor inlet and outlet pressures and reactor pressure drop are shown in Figure 41 (a) to Figure 41 (c). Once again, the mass flow transient did not produce differences in the two solutions. However, the pressure increase due to control rod withdrawal is overestimated by the reference solution. The system pressure of the reference solution also settles at a higher value after the control rod insertion.

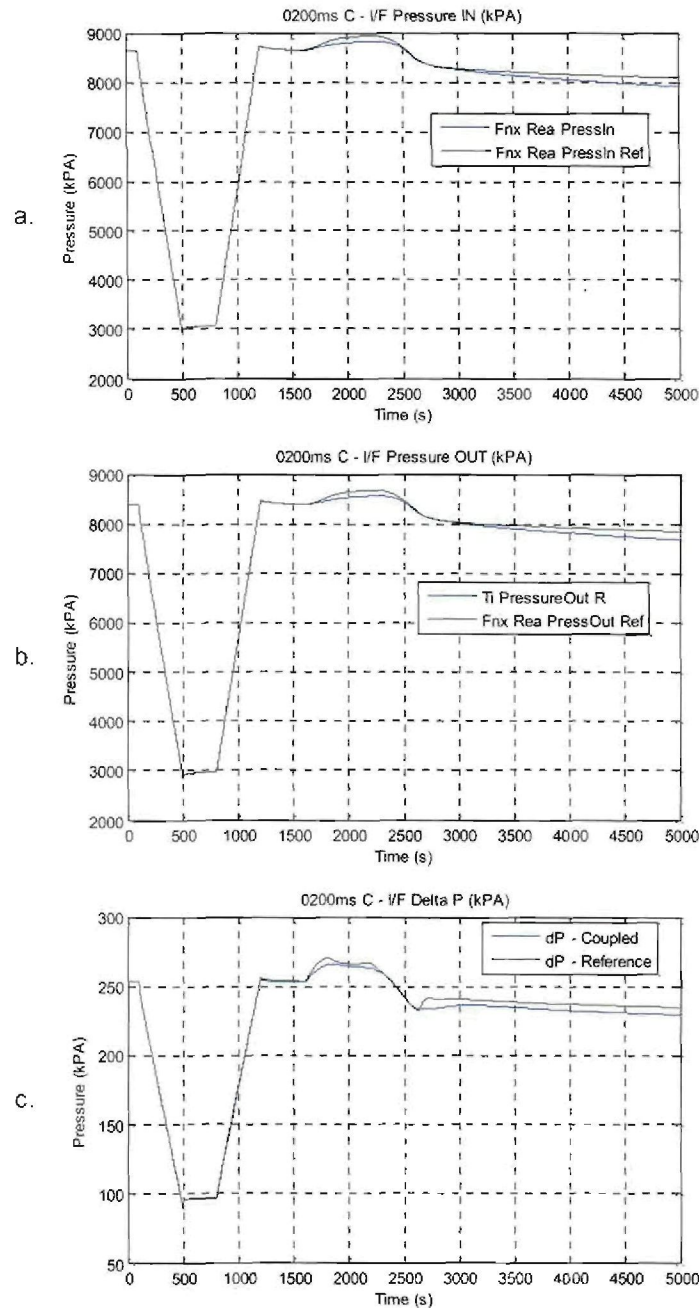


Figure 41: Solved Pressure Transient – 200 ms (Continued)

The reactor inlet and outlet temperatures are shown in Figure 42 (a) and Figure 42 (b) respectively. Again, during the mass flow transient, little differences can be seen. In contrast, the control rod transient produced massive differences in reactor outlet temperatures of close

to 50 °C, which also influences the reactor inlet temperature conditions. During control rod withdrawal, the reactor outlet temperature is hugely overestimated by the reference MPS model as a result of the spatial limitations of the point kinetics. Because the control rods are inserted deeper into the core than the initial full-power setting, the final reactor outlet temperature is also different.

The temperature difference across the reactor is shown in Figure 42 (c). The fluidic power in the MPS is directly related to it, as well as to the mass flow. Big differences in shaft excess power can therefore also be expected for the control rod transient.

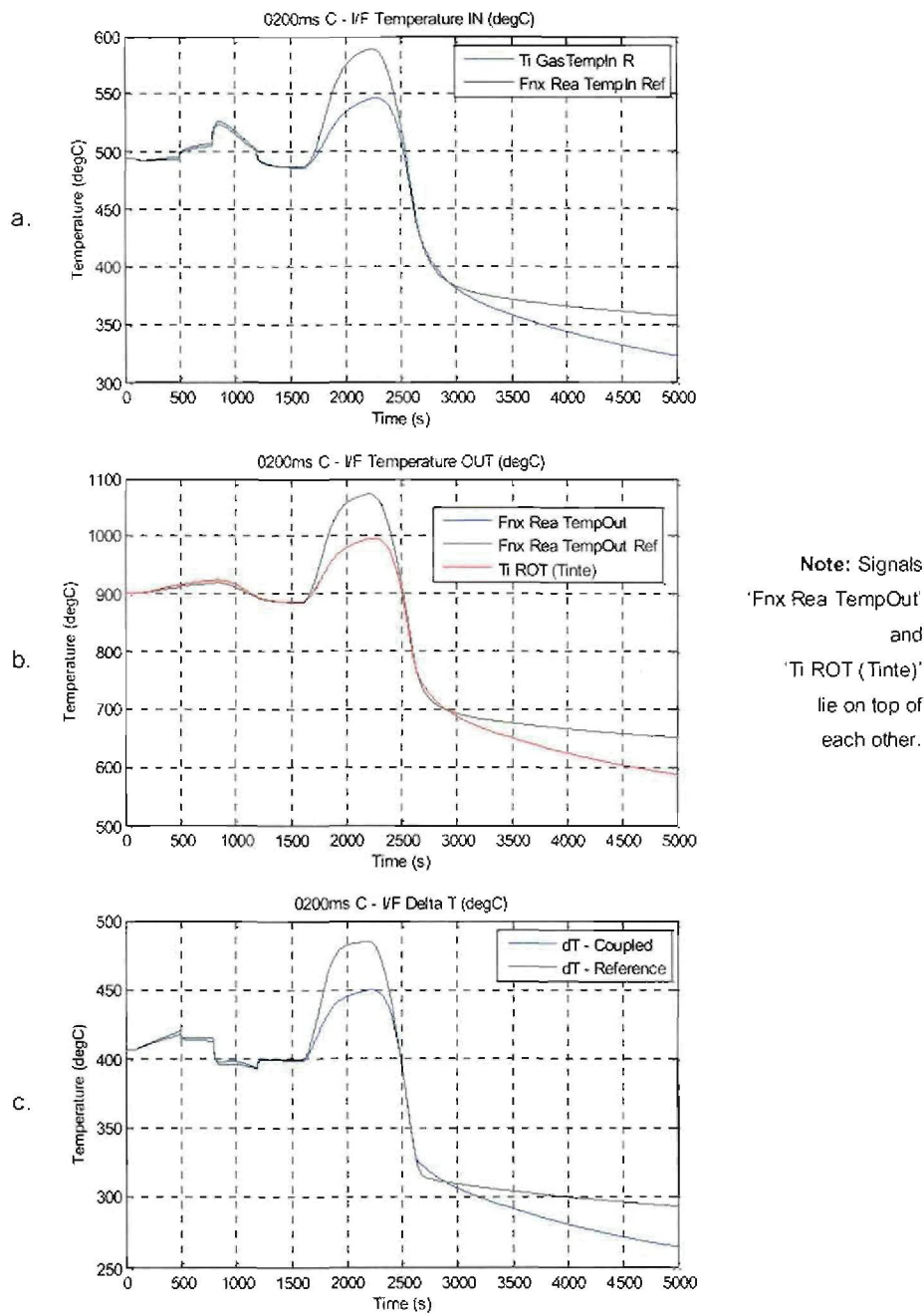


Figure 42: Solved Pressure Transient – 200 ms (Continued)

The reactor core temperatures are shown in Figure 43 (a). The most critical value in all design and safety analysis calculations is probably the maximum fuel temperature, which is calculated by TINTE alone. The average fuel and moderator temperatures for the two reactor models can be compared. Note the higher prediction for these temperatures by the reference solution from the start. The differences are more pronounced during and after the control rod transient.

The shaft excess power can be seen in Figure 43 (b). During the mass flow transient, virtually no differences can be seen. However, during and after the control rod transient, there are major differences as predicted due to the error in reactor outlet temperature.

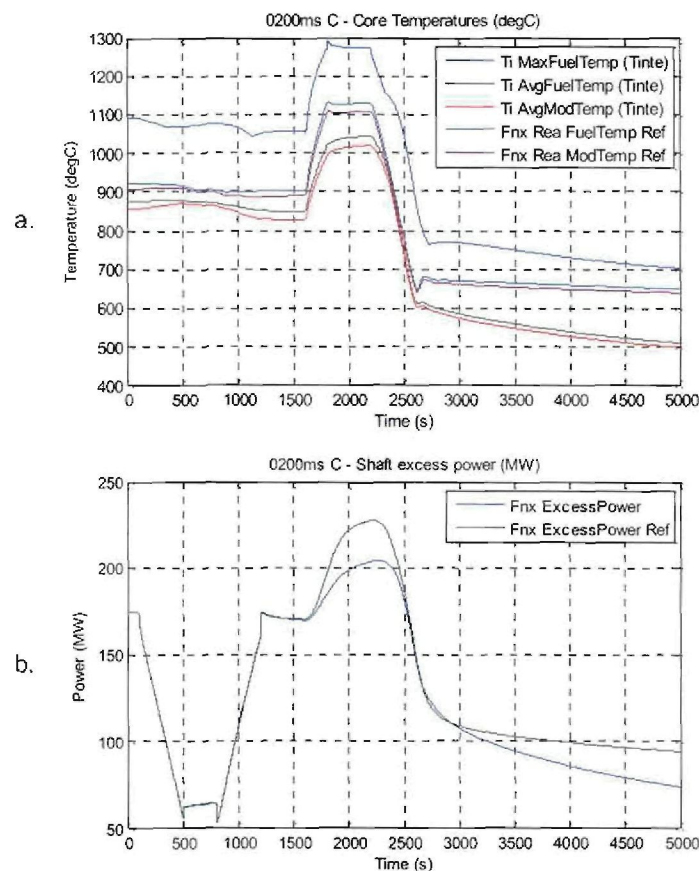
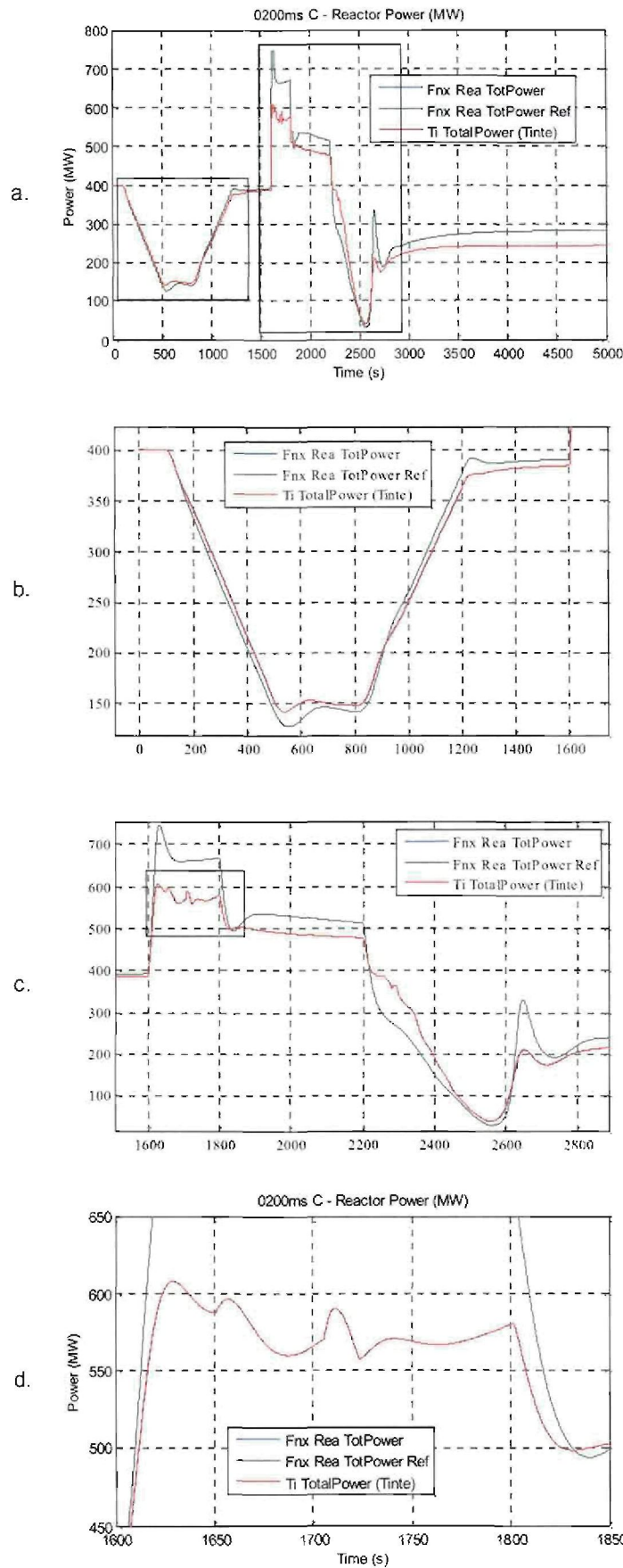


Figure 43: Solved Pressure Transient – 200 ms (Continued)

Reactor power is directly affected by the mass flow quantity and control rod position. Figure 44 (a) shows the reactor total power for the combined transient. This graph only shows the difference in reactor total power between TINTE and the reference solution. However, all preceding graphs show the effect that it has on the closed-loop MPS.

The amplified mass flow transient region (Figure 44 (b)) shows approximate differences of up to 15% for low power, and again 5% when the inventory is restored to full-power conditions. The control rod transient region (Figure 44 (c)) shows much larger differences of approximately 20% during control rod withdrawal and 50% after control rod insertion.



Note: Signals
'Fnx Rea TotPower'
and
'Ti TotalPower (Tinte)'
lie on top of
each other.

Note: Signals
'Fnx Rea TotPower'
and
'Ti TotalPower (Tinte)'
lie on top of
each other.

Note: Signals
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'Ti TotalPower (Tinte)'
lie on top of
each other.

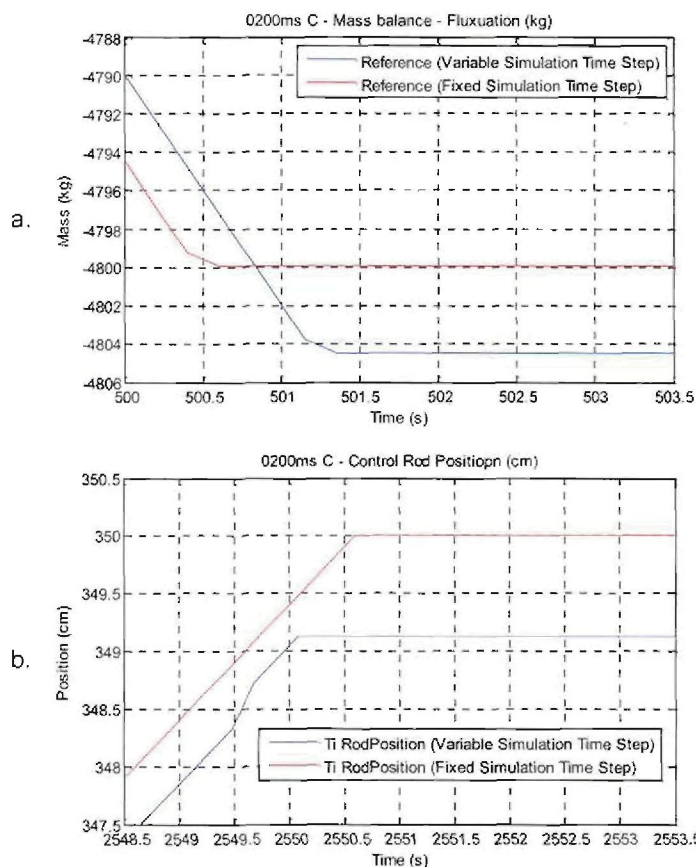
Note: Signals
'Fnx Rea TotPower'
and
'Ti TotalPower (Tinte)'
lie on top of
each other.

Figure 44: Solved Pressure Transient – 200 ms (Continued)

Note the wiggles in the TINTE calculated total power between 1 600 s and 1 800 s (Figure 44 (d)). This is non-physical and can be corrected by modelling the non-linear relationship between poison concentration and control rod position within the TINTE model more accurately. All control rod movements with TINTE has been done using the Linear Rod Motion Model (ROMO) option, which is based on the model of equivalent neutron poisoning in annular regions. An interpolation factor needs to be determined beforehand for each annular region that can have partially inserted rods or Small Absorber Spheres (SASs). The current TINTE model uses default interpolation factor values for all control rod and SAS annular regions. [5]

5.4.2 Variable Simulation Time Steps

The same mass flow and control rod transient used for the case of Section 5.4.1 was repeated here, but using a variable simulation time step. It was limited between 200 ms and 2 000 ms. Due to the simple algorithm employed for variable time-step logic, exact repetition of the comparison case of Section 5.4.1 was not possible. However, it was close enough to demonstrate the concept. Figure 45 (a) shows the timing difference for the inventory change and Figure 45 (b) the same for the control rod movement.



Note:
Refer
Figure 38.

Note:
Refer
Figure 39.

Figure 45: Solved Pressure Transient – 200 ms and Variable

The fixed and variable simulation time step cases can be seen in Figure 46 (a). The variable simulation time step varies between 200 ms and 2 000 ms. For the sake of smooth integrations to be performed by the models, the variable simulation time step was minimized before the transient started or ended. An amplified region where the control rod withdrawal took place is shown in Figure 46 (b). Note the sudden decrease of the variable simulation time step to 200 ms just before it started at 1 600 s. The algorithm then increased the variable simulation time step to 400 ms based on its monitoring logic. At 1 800 s, it started to increase as the control rods stopped to move, but soon after, some quirk in the timing logic forced it to 200 ms again. It then increased slowly to 2 000 ms, where it stayed until the end.

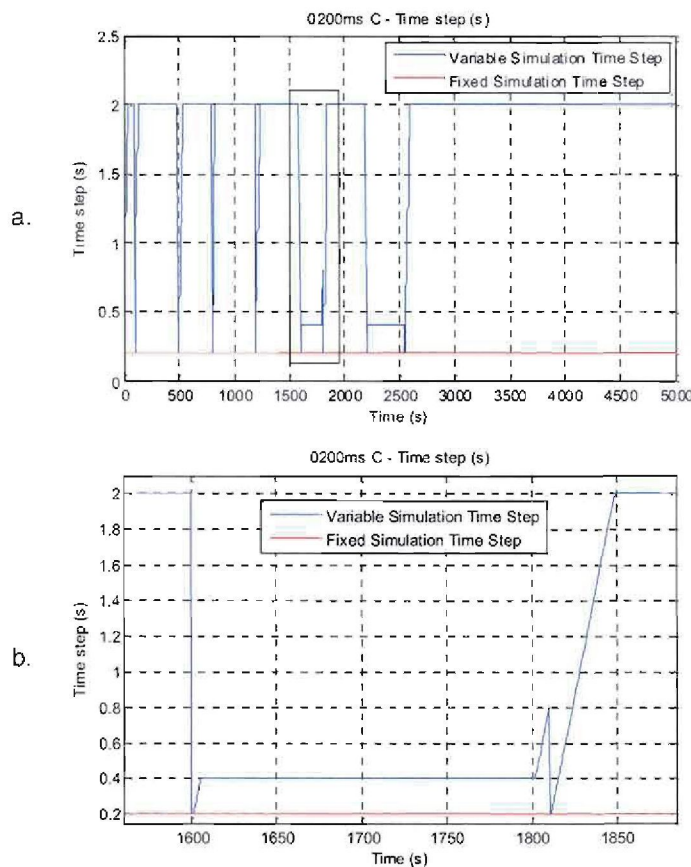
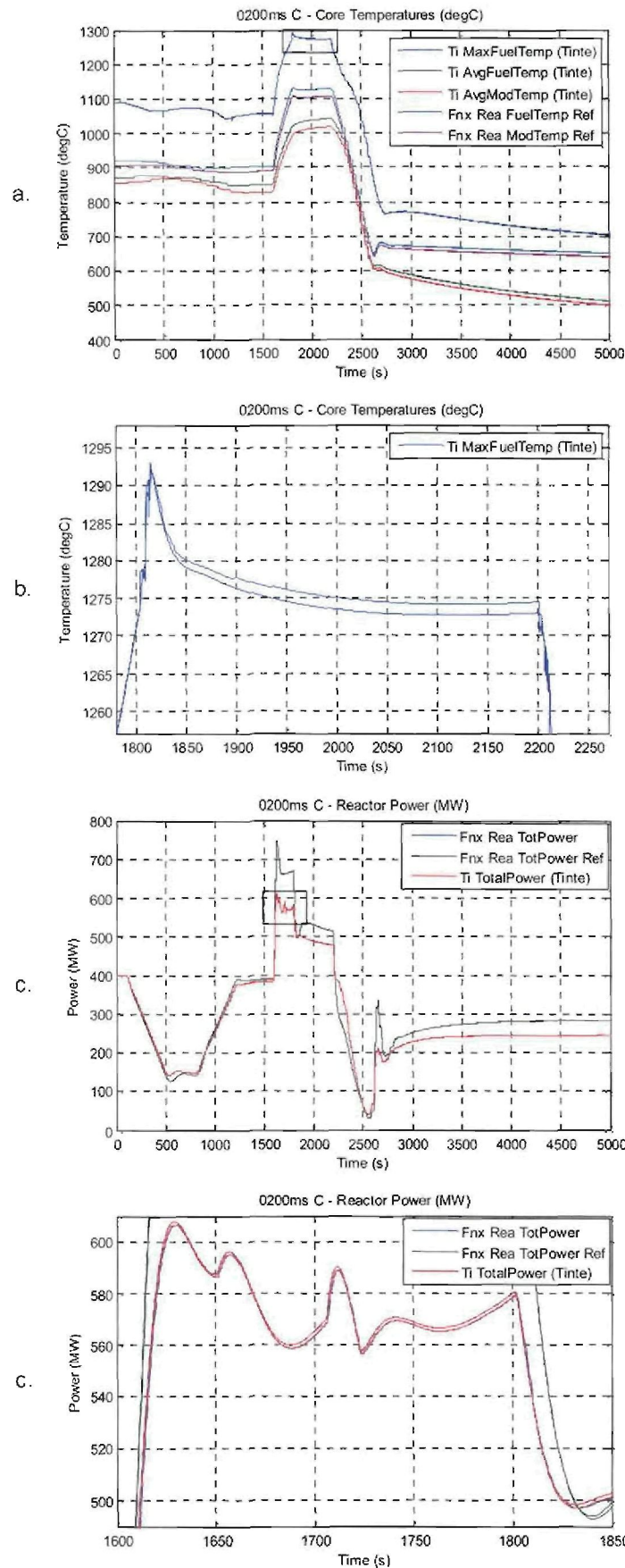


Figure 46: Solved Pressure Transient – 200 ms and Variable (Continued)

The monitored variables were core temperatures (Figure 47 (a)) and reactor total power (Figure 47 (c)). Both of these sets of values showed very good correlations. Figure 47 (b) and Figure 47 (d) shows the amplified region where the control rod withdrawal took place.

Measurements between the fixed and variable simulation time-step cases were done for a total simulation time of 10 000 s. The fixed case took 50 000 simulation steps and ~81.81 h, whereas the variable case took 6 354 simulation steps and ~ 15.83 h. A speed-up of ~5.2 times was realized while still producing acceptable results, as shown in Figure 47.



Note: Two cases using the same colours for the same signal are shown here for comparison.

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Figure 47: Solved Pressure Transient – 200 ms and Variable (Continued)

5.5 CONCLUSION

A fixed pressure transient was successfully performed using the external Flownex Nuclear/Flownex Nuclear coupling. No instabilities occurred when using a simulation time step of 1 000 ms. When the coupling signals were filtered, a simulation time step of 100 ms was feasible with stable results. The ability to perform this coupling successfully is important to set up a large integrated simulation scenario consisting of multiple Flownex Nuclear models.

The external TINTE/Flownex Nuclear coupling, also with a fixed pressure transient, was successfully demonstrated with equally good results as the Flownex Nuclear/Flownex Nuclear coupling. However, a smaller simulation time step is required for stable calculations. The benefit of this coupling is the availability of the TINTE calculated reactor outlet temperature as part of the coupled closed-loop behaviour.

A solved pressure transient could only be performed with the parallel TINTE/Flownex Nuclear coupling. For this coupling, stability is as good as the individual codes used, not worse, and there are virtually no time delay effects to spoil the closed-loop behaviour. Interesting results not previously available to PBMR (Pty) Ltd could be shown for the hypothetical test case. The effect of having a more accurate, albeit combined, reactor model influenced the closed-loop MPS behaviour substantially.

The indirect cost of performing integrated simulation scenarios is important. A simple but effective variable simulation time-step algorithm applied to the parallel TINTE/Flownex Nuclear coupling was demonstrated. The test case ran for 15.83 h instead of 81.81 h with acceptable results – a speed-up of ~5.2 times was realized and was made possible by the flexible architecture of the NEA Simulator.

6. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

The aim of this research has been met: to gain a fundamental understanding of the external coupling of time-dependent multi-physics code systems, and to establish a platform to integrate and coordinate these types of analyses. The basic software infrastructure required to conduct the research was developed in a relatively short time. It was based on a CORBA-based simulator architecture provided by PBMR (Pty) Ltd, and is now called the NEA Simulator.

The literature survey uncovered three basic types of coupling methodologies, of which external explicit and parallel proved to be the most viable candidates to implement and test on the NEA Simulator. Stability problems with the intended external coupling were predicted and have been found. However, these were not insurmountable and the limits of their applicability are well documented in this research.

Some of the modifications required to establish the NEA Simulator involved removing a superfluous hosting software interface, simplifying the GUI, developing a new interface to TINTE, and enhancing the simulation control and scheduling capabilities. The NEA Simulator facilitates large, integrated and distributed simulations. It is currently actively being used for TINTE/Simulink simulations, and is nearly production ready for TINTE, multiple Flownex Nuclear and Simulink integrated simulations.

The progressive development of the integrated simulation uncovered interesting behaviour of the coupled systems. Contrary to what was expected, the stability of the Flownex Nuclear/Flownex Nuclear external coupling improved with larger simulation time steps. By introducing low-pass filtering to the coupling signals, stability could be restored at smaller time steps. The external coupling of TINTE/Flownex Nuclear was also successful and stability was achieved when reducing simulation time steps, as expected.

The explicit external coupling of two open-loop thermal-fluid models with circular dependencies produced acceptable results for fixed pressure transients. However, when solving for pressure during a transient, this methodology is fundamentally flawed without introducing correction terms such as the semi-implicit coupling technique. (The latter was not attempted in this research.) With the explicit external coupling of TINTE and Simulink, there are no circular thermal-fluid dependencies between the two models, and the resulting closed-loop system is stable within the dynamic bounds of gain and phase margins.

The parallel coupling of TINTE and the closed-loop Flownex Nuclear MPS model proved to be the most successful. It is by far the most stable and versatile coupling analysed in this research.

Some important building blocks were put in place to achieve the goal of simulating all plant modes and transitions involving the reactor on a continuous basis. One of these is the ability to couple multiple Flownex Nuclear models, which was demonstrated successfully. The requirement to influence the MPS behaviour with TINTE-calculated reactor outlet temperature and total power can now also be fulfilled. The parallel TINTE/Flownex Nuclear coupling provides good coupling stability and the ability to solve pressure during transients with virtually no time delay in the closed loop behaviour. The indirect cost of performing integrated simulation scenarios is also important, and variable simulation time steps to accelerate the simulation were demonstrated. This was made possible by the flexible architecture of the NEA Simulator. Resiliency of an integrated simulation is critical, and local time-step management for the TINTE temperature solver on a continuous basis is implemented in the TINTE–NEA Simulator interface.

Recommendations for further research involve:

- Verifying that the external TINTE/Flownex Nuclear coupling also does not conserve mass for transients where pressure is solved.
- Coupling of two open flow loops with the semi-implicit coupling technique of [13].
- Extending the external control interface of Flownex Nuclear to accept 2D spatially dependent power profile values for its reactor model instead of the current single total reactor power value.
- Introducing of a hybrid parallel indirect coupling between the TINTE, Flownex Nuclear reactor and Flownex Nuclear PCU models.

This further development of the parallel coupling would be to split the Flownex Nuclear MPS model into the reactor and PCU in such a way that the stability characteristics of the former would be retained. Similar approaches to the indirect coupling performed in [8] and [9] should be used. The result would be a parallel coupling between TINTE and the Flownex Nuclear reactor model and an indirect coupling between the Flownex Nuclear reactor and PCU models.

The suggested further research will result in less expensive integrated simulations with more flexibility to simulate all plant modes and transitions involving the reactor on a continuous basis. If Flownex Nuclear can accept 2D spatially dependent power profile values as input the reactor outlet temperature calculation will also be more accurate.

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