STEADY-STATE AND ACCIDENT ANALYSES OF PBMR WITH THE COMPUTER CODE SPECTRA

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ABSTRACT

The SPECTRA code is an accident analysis code developed at NRG. It is designed for thermal-hydraulic analyses of nuclear or conventional power plants. The code is capable of analysing the whole power plant, including reactor vessel, primary system, various control and safety systems, containment and reactor building. The aim of the work presented in this paper was to prepare a preliminary thermal-hydraulic model of PBMR for SPECTRA, and perform steady state and accident analyses. In order to assess SPECTRA capability to model the PBMR reactors, a model of the INCOGEN system has been prepared first. Steady state and accident scenarios were analyzed for INCOGEN configuration. Results were compared to the results obtained earlier with INAS and OCTOPUS/PANTHERMIX. A good agreement was obtained. Results of accident analyses with PBMR model showed qualitatively good results.

It is concluded that SPECTRA is a suitable tool for analyzing High Temperature Reactors, such as INCOGEN or for example PBMR (Pebble Bed Modular Reactor). Analyses of INCOGEN and PBMR systems showed that in all analyzed cases the fuel temperatures remained within the acceptable limits. Consequently there is no danger of release of radioactivity to the environment. It may be concluded that those are promising designs for future safe industrial reactors.

1. INTRODUCTION

The development of High Temperature Reactors (HTR) is taking place for more than thirty years now. The major developmental activities presently proceeding for introduction of HTR power systems are the 600 Gas Turbine - Modular Helium Reactor (GT-MHR), and the 268 MWth Pebble Bed Modular Reactor (PBMR). PBMR is currently planned to be built in the Republic of South Africa.

An HTR pre-feasibility study has been performed in the past in the Netherlands[1], using a 40 MWth base configuration, named INCOGEN. A number of analyses were performed for the INCOGEN configuration, including steady-state and accident scenarios performed with INAS and PANTHERMIX/OCTOPUS codes.

Nuclear Research and Consultancy Group (NRG) is participating in the PBMR project, performing design and safety analyses. The aim of the work presented in this paper was to prepare a preliminary thermal-hydraulic model of PBMR for the computer code SPECTRA[2], and perform steady state and accident analyses. In order to assess SPECTRA capability to model the PBMR reactors, a model of the INCOGEN system has been prepared first. Steady state and accident scenarios were analyzed for INCOGEN configuration. Results were compared to the results obtained earlier with INAS and OCTOPUS/PANTHERMIX.

The first part of this paper presents comparison of SPECTRA results obtained for INCOGEN, for steady state cases and two accidents: Loss of Coolant Accident (LOCA), and Loss of Flow Accident (LOFA) with the results of the INAS and OCTOPUS/PANTHERMIX codes. The second part presents results of steady state calculations as well as LOCA and LOFA cases obtained with the preliminary SPECTRA model of PBMR.

2. SPECTRA CODE AND IT'S APPLICABILITY FOR PBMR

The SPECTRA code is an accident analysis code developed at NRG, the Netherlands. SPECTRA (Sophisticated Plant Evaluation Code for Thermal-hydraulic Response Assessment)[2], is a computer program designed for thermal-hydraulic analyses of nuclear or conventional power plants. The code is capable of analysing the whole power plant, including reactor vessel, primary system, various control and safety systems, containment and reactor building. The models applied in the code were selected after an extensive literature review, as well as review of models available in other codes (CONTAIN, MAAP, MELCOR, RELAP, TRAC-BF1). The best available models were selected, which makes SPECTRA not only an accident analysis tool but also a library of physical models, well documented and tested, and easy to use.

In case of PBMR an important issue is the ability of a computer code to model multiple non-condensable gases, in particular helium. In contrast to codes like RELAP, TRAC, which are basically steam-water codes, SPECTRA has been built to allow presence of a mixture of multiple gases. SPECTRA contains a built-in library of fluid properties, consisting of the properties of water, steam, and non-condensable gases, such as H_2, He, N_2, O_2, CO_2. The gas properties are calculated using a large database, covering the range from 270 K to 2070 K, and from virtually 0 Pa to 10^7 Pa. If needed, properties of other gases may be easily implemented into the program. The solution scheme is general, and may theoretically accommodate any number of gases. Practical limit is imposed by the physical memory size of the computer designated to perform calculations.

A reactor kinetics model together with an isotope transformation model are present in the SPECTRA code. They are suitable for simple (point kinetics) analysis of reactivity transients. The isotope transformation model can deal with 200 isotopes; typically about 30-40 isotopes are tracked, including fuel chains, main poisons, such as Xe-135, Sm-149, and their precursors, as well as main decay heat producers.

3. INCOGEN Analyses - Comparison with INAS, OCTOPUS/PANTHERMIX

This section provides description of the steady state and accident analyses performed for the High Temperature Reactor (HTR), the conceptual design of INCOGEN. All data required to build the SPECTRA model of the INCOGEN reactor was obtained from reference [1]. The SPECTRA model of the INCOGEN reactor is shown in figure 1. The model consists of 8 Control Volumes (CV), 7 Junctions (JN), 9 Solid Heat Conductors (SC). The net enclosure thermal radiation model is used, with two enclosures: the reactor core (TR-101 - TR-105), and the gas inlet annulus (TR-202 - TR-204). The Reactor Kinetics model is used to calculate core power.

The following calculations were performed:

- Steady state analyses:
  - Steady state run with constant power (SS-CP),
  - Steady state run with reactor kinetics, reactivity control by continuous fuel addition (SS-RK-1).
  - Steady state run with reactor kinetics, reactivity control by temperature changes (SS-RK-2).
- Accident analyses:
  - Loss of Flow Accident (LOFA).
  - Loss of Coolant Accident (LOCA).

The first steady state calculation was performed using a constant reactor power. This was done just to obtain a good starting point for the subsequent analyses with the reactor kinetics model. The next two steady state analyses were performed using two different methods of reactivity control. First, the reactivity was controlled by a continuous fuel addition (SS-RK-1). Fuel addition rate was controlled in order to keep the desired reactor power. In the next run (SS-RK-2) no fuel was added to the core. The reactivity loss due to slow fuel burn-up was compensated by a slow temperature decrease, which added reactivity due to negative reactivity coefficient. Results of these two runs are compared to the results of the INAS code (presented in reference [1]) in figures 2 and 3.

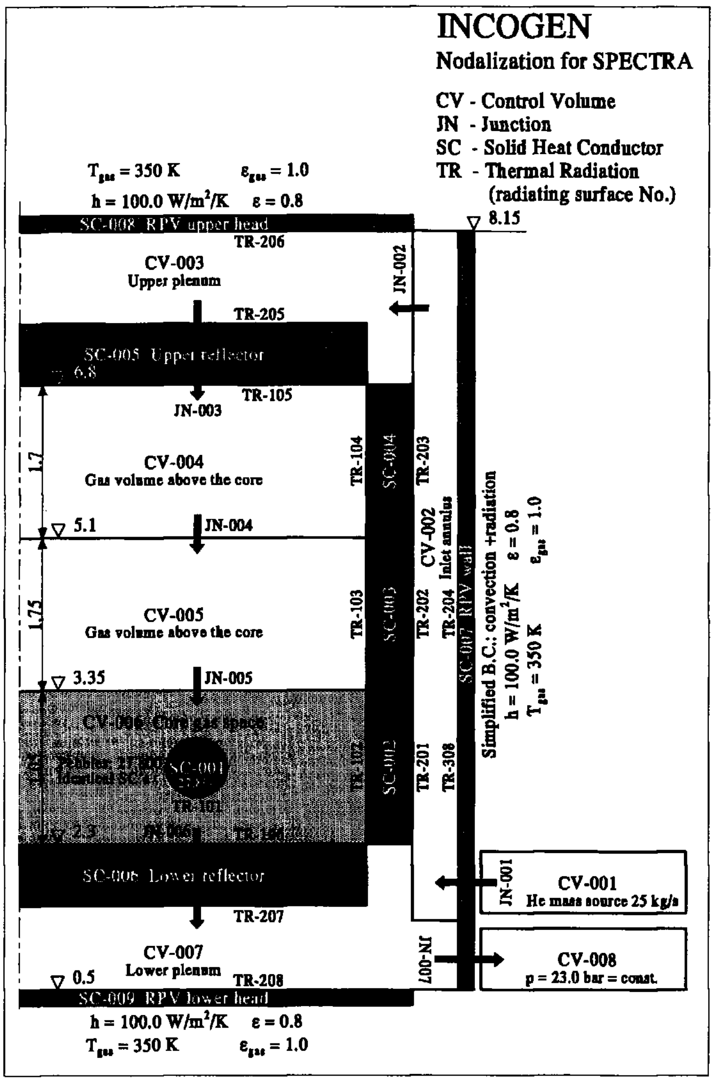

Figure 1
SPECTRA model of the INCOGEN reactor.

Figure 2 shows the fuel loading rate in case SS-RK-1. The SPECTRA calculated stable value of fuel loading rate is equal to about 10^{-8} [s^{-1}], a little more than 20 pebbles per day. The value obtained from the INAS code for the fresh core configuration is equal to 48 pebbles per day, more than twice more than the SPECTRA value. This discrepancy is caused by a non-uniform neutron flux distribution (no upper reflector), which cannot be taken into account with the point kinetics model. The neutron flux in the upper part of the core is nearly twice smaller than in the lower part of the core. The fresh pebbles, landing on the top of the core, therefore "see" only relatively small neutron flux and therefore their reactivity worth is significantly smaller than it would be if the neutron flux was uniform (as it is, by definition, in the point kinetics model). Consequently, more pebbles are needed to maintain criticality than it is predicted by the point kinetics model. In case of PBMR reactor the neutron flux is much more uniform and the point kinetics provides more accurate results (see section 4).

Figure 3 shows core average temperature during the second day of the SS-RK-2 run. The temperature decreases steadily, with the rate of about 7.1 K per day. The value obtained from the INAS code is 7.8 K per day. The agreement between SPECTRA value and the value from INAS is in this case relatively good.

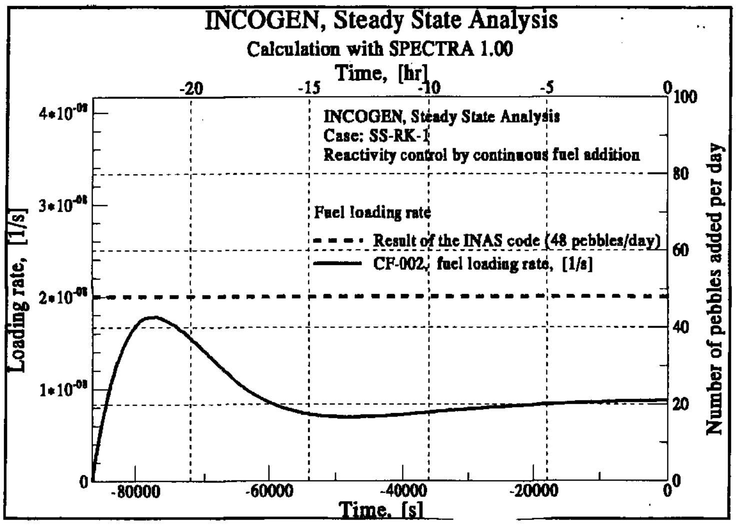

Figure 2
Fuel loading rate, INCOGEN, Case SS-RK-1, continuous fuel addition, comparison of SPECTRA and INAS results.

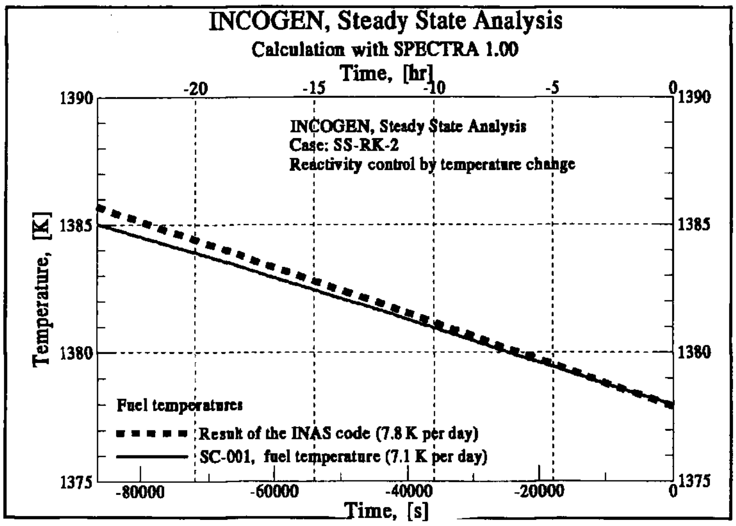

Figure 3
Core average temperature, INCOGEN, Case SS-RK-2, no fuel addition, comparison of SPECTRA and INAS results.

Results of accident analyses are shown in figures 4 - 9. The reactivity calculated for the LOFA case by the OCTOPUS/PANTHERMIX code and the SPECTRA code are compared in figures 4 and 5. Both result are in good agreement as to the depth and the duration of the "reactivity well". The reactivity behavior in OCTOPUS/PANTHERMIX show some irregularities around 500 min and 900 min (figure 4), the nature of which are not quite clear. Probably they are a consequence of some space dependent effects, that cannot be captured with point kinetics.

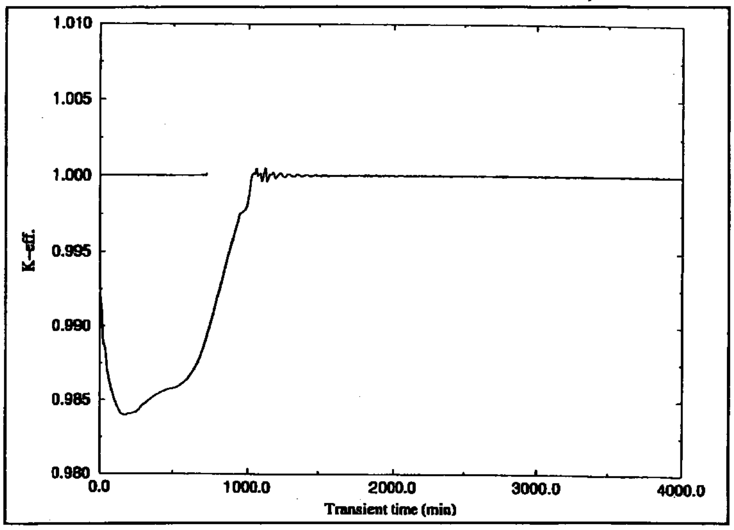

Figure 4
Total reactivity, INCOGEN, Case: LOFA, Loss of Flow Accident, results of OCTOPUS/ /PANTHERMIX code system (reproduced from reference [1].

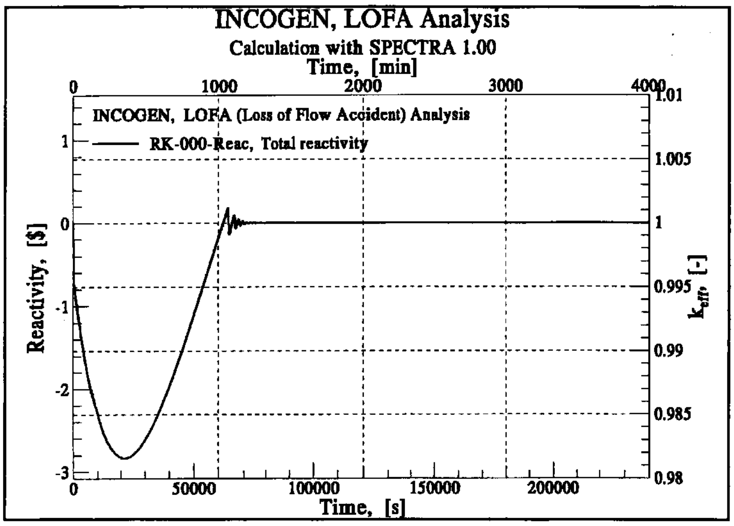

Figure 5
Total reactivity, INCOGEN, Case: LOFA, Loss of Flow Accident. SPECTRA results.

Figures 6 and 7 show reactor power calculated for both LOFA and LOCA cases by OCTOPUS/PANTHERMIX and SPECTRA respectively. Generally the agreement is very good. In SPECTRA the power peaks occurring just after reaching criticality are higher, but the OCTOPUS/PANTHERMIX results indicate that the peaks might have been flattened by rare plot frequency. OCTOPUS/PANTHERMIX show somewhat oscillating long term reactor power for LOFA case. The nature of this oscillations are unclear. Possibly they are created by some numerical problems (for example explicit coupling between the codes which constitute the OCTOPUS/PANTHERMIX code system). These oscillations should be distinguished from the oscillations which occur just after reaching criticality, and are observed in all calculations. These are rather regular oscillations, with the time period close to 2000 s (half an hour). Those oscillations are physical and are caused by inertial effects in thermal-neutronic interactions.

In both LOCA and LOFA cases the calculated maximum fuel temperature remained within acceptable limits. In all calculations the fuel temperature did not exceed 1500°C.

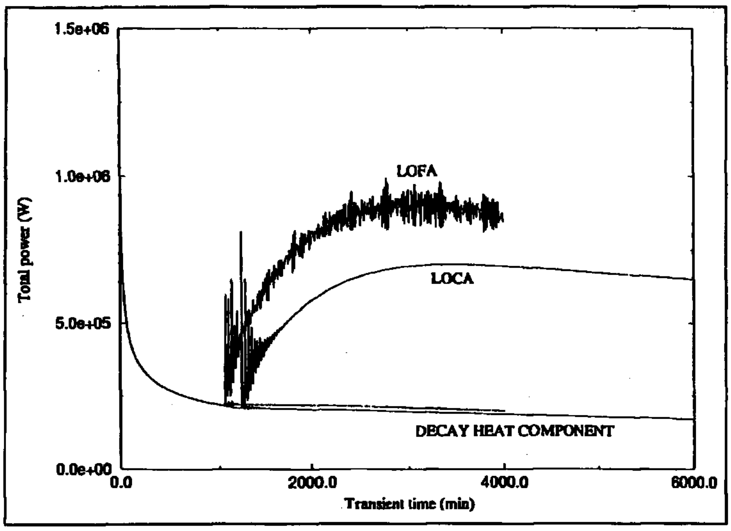

Figure 6
Reactor power, INCOGEN, Cases: LOFA and LOCA, results of OCTOPUS/ /PANTHERMIX code system (reproduced from reference [1]).

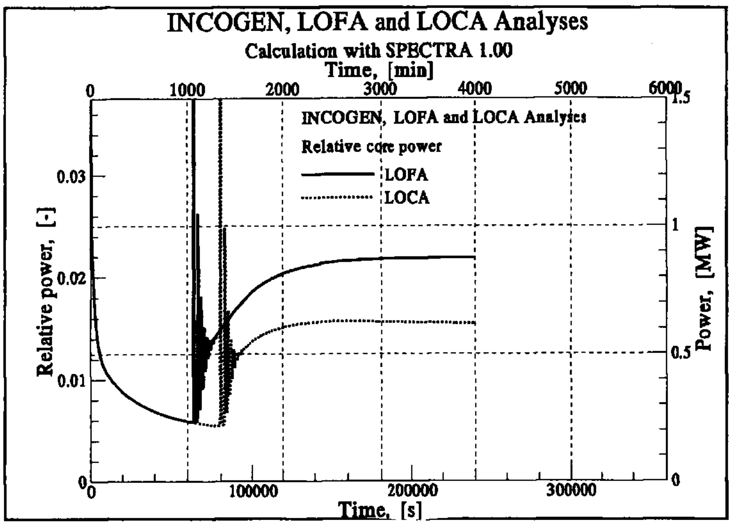

Figure 7
Reactor power, INCOGEN, Cases: LOFA and LOCA, SPECTRA results.

4. PBMR ANALYSES

SPECTRA model of PBMR[3] is shown in figures 8 and 9. The model includes the Reactor Unit (figure 8), the Power Conversion Unit (figure 9), the Confinement Building, as well as various safety systems and the environment. The model is considered to be preliminary. Some parts of the system were modelled in a simplified way because no sufficient data were available at NRG. In the future the model will be updated according to the most recent data and design drawings. This task will be performed within the cooperation between the South African PBMR and NRG.

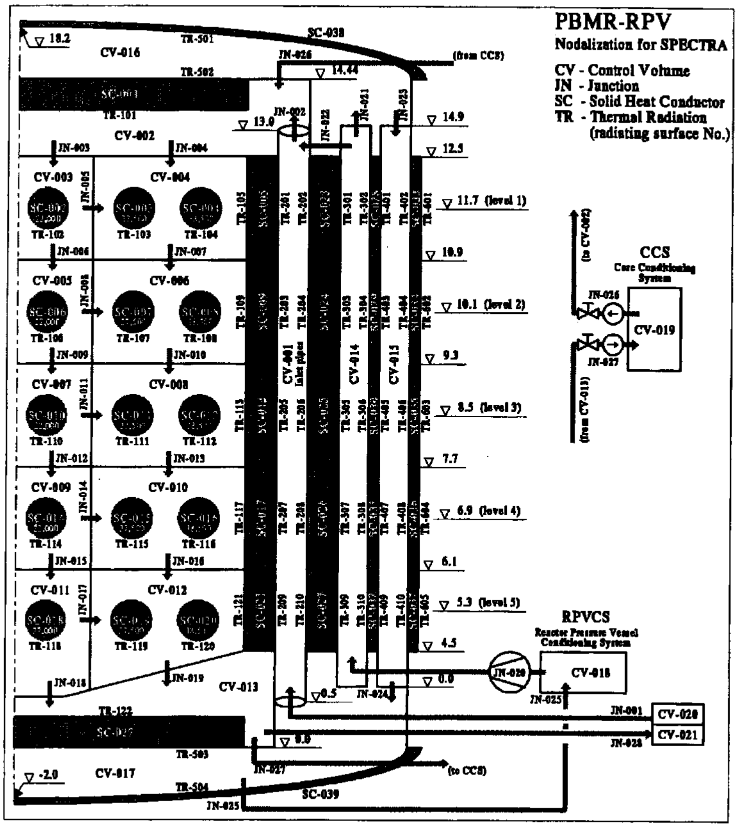

Figure 8
SPECTRA model of PBMR.
Nodalization of the Reactor Unit.

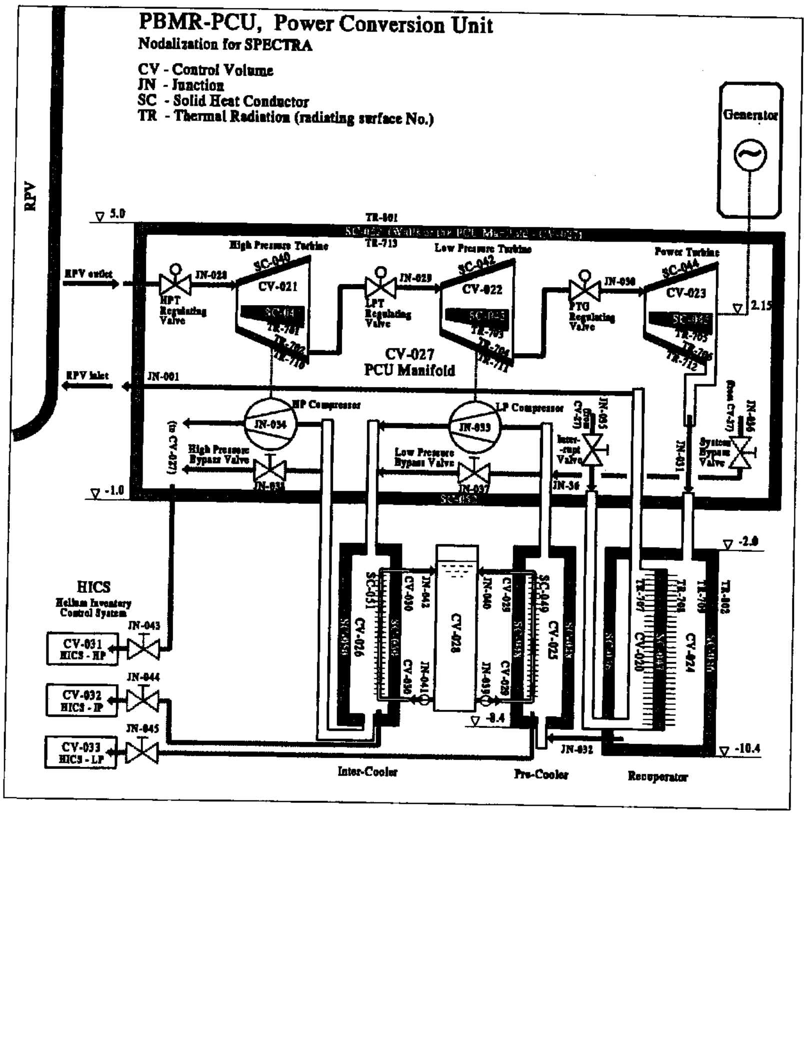

Figure 9
SPECTRA model
of PBMR.
Nodalization of the Power
Conversion Unit.

As in case of INCOGEN, steady state and accident analyses (LOCA and LOFA) were performed with the model. Steady state calculation was performed using continuous fuel reload to control reactivity. Resulting fuel reload rate is shown in figure 10. SPECTRA results are compared with the values obtained with PATHERMIX and VSOP codes, reported in [4]. The calculated reload rates are in good agreement. (The initially higher reload rate in SPECTRA was needed to overcome some small initial changes in Xenon concentration, resulting from imperfections in defining the initial conditions.)

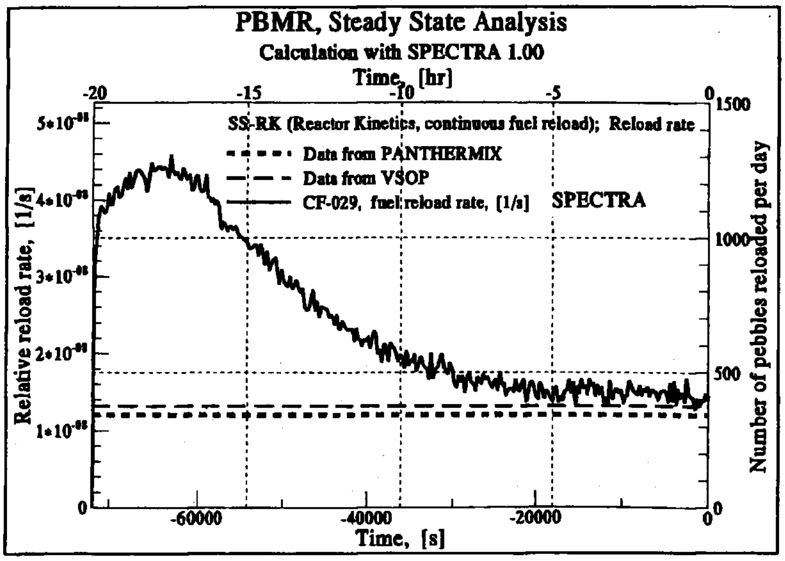

Figure 10
Fuel reload rate, PBMR, comparison of SPECTRA PANTHERMIX and VSOP results.

The results of the LOCA and LOFA analyses are shown in figures 11 and 12. The main difference between LOCA and LOFA cases is the system pressure during the major part of the transient (about 70 bar in case of LOFA and atmospheric in case of LOCA). In the high pressure case a relatively good natural circulation flow was developed, and some heat was removed by the pre-cooler and the inter-cooler. As a consequence the fluid temperature was lower in LOFA and the reactivity was higher (negative temperature reactivity coefficient). The depth of the "reactivity well" was smaller in case of LOFA, and criticality was reached faster (figure 11). After criticality was reached, the power stabilized at higher level in case of LOFA, since more power was removed by the pre- and the inter-cooler. In the accident scenarios it was assumed that pumps cooling the secondary side of the coolers were available (the only available active systems). If these pumps were unavailable the difference between LOCA and LOFA would be smaller.

In both LOCA and LOFA cases the calculated maximum fuel temperatures were below 1400°C - within acceptable limits.

5 SUMMARY AND CONCLUSIONS

Steady state operation and accident scenarios were analyzed with the SPECTRA code for the INCOGEN and the PBMR reactors. In case of INCOGEN the results of steady state analyses were compared to the results of the INAS code. A good agreement was obtained for the run with reactivity control by temperature changes. In case of reactivity control by continuous fuel addition a discrepancy was found in the fuel addition rate. It was found out that the discrepancy was caused by strongly nonuniform neutron flux distribution in the INCOGEN core, a phenomenon that cannot be represented with the point kinetics model.

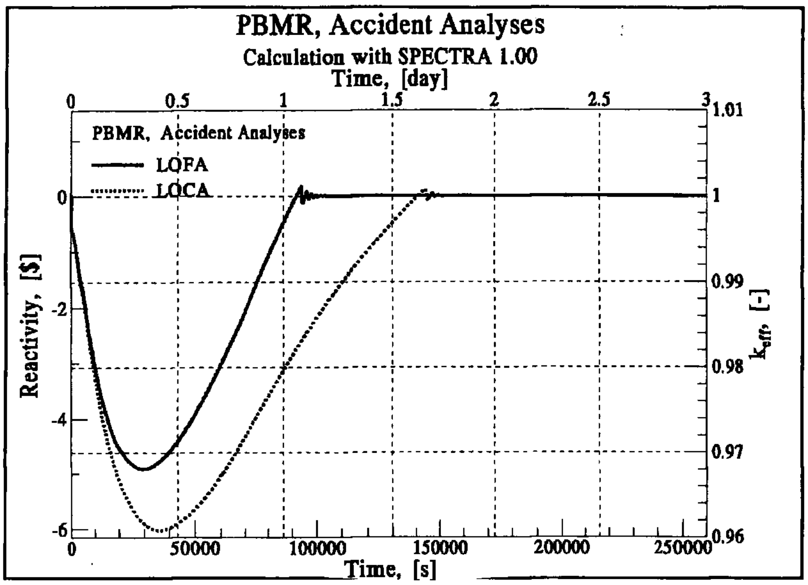

Figure 11
Total reactivity, PBMR
Cases: LOFA and LOCA,
SPECTRA results.

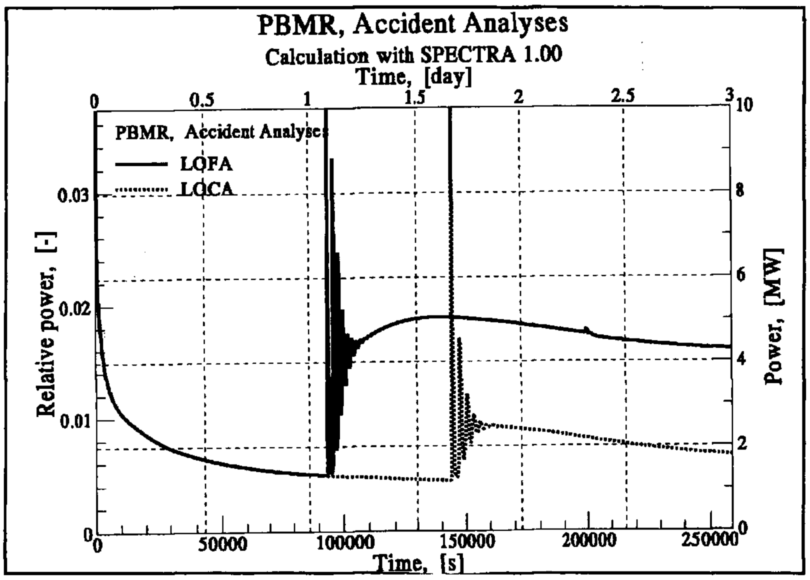

Figure 12
Reactor power, PBMR,
Cases: LOFA and LOCA,
SPECTRA results.

In case of PBMR the results of steady state analysis were compared to the results of the PANTHERMIX and VSOP codes. A good agreement was obtained. In PBMR the core is relatively uniform because of continuous fuel reload and mixing, and the point kinetics model gives satisfactory results.

Results of accident analyses with the INCOGEN model were compared with the results of OCTOPUS/PANTHERMIX code system. Generally a very good agreement was obtained. Results of accident analyses with PBMR model showed qualitatively qood results. Further improvement in the detail of modelling is needed to provide reliable results.

It is concluded that SPECTRA is a suitable tool for analyzing High Temperature Reactors, such as INCOGEN or for example PBMR (Pebble Bed Modular Reactor).

Analyses of INCOGEN and PBMR systems showed that in all analyzed cases the fuel temperatures remained within the acceptable limits. Consequently there is no danger of release of radioactivity to the environment. It may be concluded that those are promising designs for future safe industrial reactors.

References

[1] A.I. van Heek, et al., "INCOGEN Pre-Feasibilty Study", ECN report, PINK 1997, September 1997.

[2] M.M. Stempniewicz, "SPECTRA - Sophisticated Plant Evaluation Code for Thermal-hydraulic Response Assessment, Version 1.00; Volume 1: Program Description; Volume 2: User's Guide, Volume 3: Description of Subroutines; Volume 4: Verification", 26094-/99.52612/C, NRG report, Arnhem, October 1999.

[3] M.M. Stempniewicz, K. Spijker, "Development and Verification of SPECTRA Model of PBMR", NRG report, 20352/01.52091/C, Arnhem, February 2001.

[4] H.T. Klippel, et al., "PBMR Burn-in Core Analysis - PBMR Benchmark with PANTHER-MIX", NRG report 20429/00.38175/C (Rev. 1), Petten, December 2000.