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Overall aspects of control of ISIS-type nuclear reactor

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Abstract - The paper describes the main aspects related to the definition of main controls required to operate an ISIS-type nuclear power reactors. ISIS is a PWR-type intrinsically safe nuclear reactor designed by ANSALDO, based on density lock concept; it presents. between the other safety functions, self-depressurization and core cooling capability for unlimited time.

Due to its specific characteristics, the ISIS reactor required the development of new control philosophy (if compared with actual nuclear power reactor) with the implementation of new control functions, for instance the density locks hot/cold interface locations control. This paper describes the main control functions implemented, their rationale, as well as the dynamic simulation performed to verify the adequacy of controls definitions.

The dynamic simulations here described refers to a step-wise power ramp of 100-90-100 (% of nominal power) and to a power ramp of 100-50-100 with a slope of 5%/min; the results obtained have shown the ISIS capability to perform such operational transients, despite its innovative design was mainly focused on intrinsically safe behaviour .

1. Introduction

The ISIS (Inherently Safe Immersed System) has been conceived and developed by ANSALDO in recent years starting from 1987 as an innovative reactor with easily understandable inherent safety features [1]. It is an integrated PWR-type reactor, completely immersed in a large pool of cold borated water, which builds up on the density lock concept originally proposed by ABB ATOM for the PIUS plant and embodies innovative ideas for enhanced passive safety. Despite its innovative conception, the ISIS reactor components are mainly based on proven technology derived from the ANSALDO experience in the field of both LWRs and LMFBRs.

The size of the reactor is small: 200 Mwe, in order to make it suitable to small electricity grids and to non-typical nuclear use, like district heating in isolated areas.

The ISIS addresses the following main safety targets:

- Reactor configuration to provide defence, primarily by prevention, against accidents with potential severe core damage.
- Self-depresurization of the Primary System, scrubbing effect of water pools and absence of significant Reactor Containment pressurization, under all accident conditions, to eliminate the risk of significant radioactive releases to the environment.

Many studies have been performed with the purpose to evaluate the safety characteristics related to such type of passive nuclear reactor [2],[3],[4]; all the analyses have shown a very promising plant behaviour even under not anticipated accident conditions and using very conservative assumptions.

In addition to safety analyses, further studies were performed to evaluate the operational characteristics of such new concept on nuclear reactor, identifying the new control function to be implemented and verifying by computer simulation the performance of the systems. This latest activities are the object of this work.

2. Plant Description

The **Inner Vessel** (fig. 1), which encloses the circulating, low boron concentration, pressurized hot water of the Primary System, is immersed in the highly borated pressurized cold water of the **Intermediate Plenum**. The Inner Vessel is provided with Wet Insulation to limit heat losses towards the Intermediate Plenum in normal operation.

The **Reactor Vessel**, which is the essential part of the pressure boundary, encloses the Intermediate Plenum and contains the Integrated Components of the Reactor Module.

The Reactor Vessel is immersed in the cold borated water of a large **Reactor Pool** at atmospheric pressure. The Reactor Vessel is not insulated; this allows heat transfer to the surrounding water of the Reactor Pool under accident conditions.

The **Pressurizer** upper portion performs the pressure control function; the lower portion contains cold water and provides additional heat transfer surface to the Reactor Pool under accident condition.

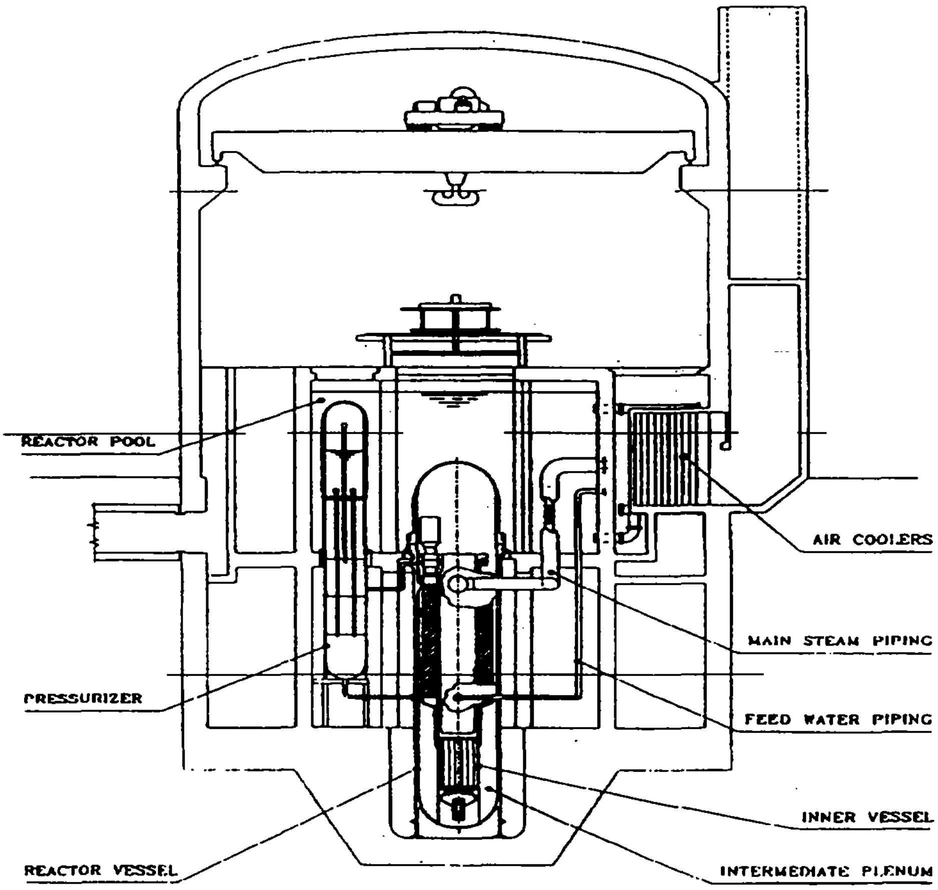

Figure 1 - ISIS Plant Arrangement

2.1 The primary System

The Primary System of the ISIS reactor is of the integrated type (fig. 2), with the Steam Generator Unit (SGU) housed in the Reactor Vessel, to which feedwater and steam piping are connected.

Within the Reactor Vessel, an Inner Vessel provided with wet metallic insulation separates the circulating low-boron primary water from the surrounding highly borated cold water.

Hot and cold plena are hydraulically connected at the bottom and at the top of the Inner Vessel by means of open-ended tube bundles, referred to in the following as Lower and Upper **Density Locks**. The Inner Vessel houses the Core, the Steam Generator Unit and the Primary Pumps.

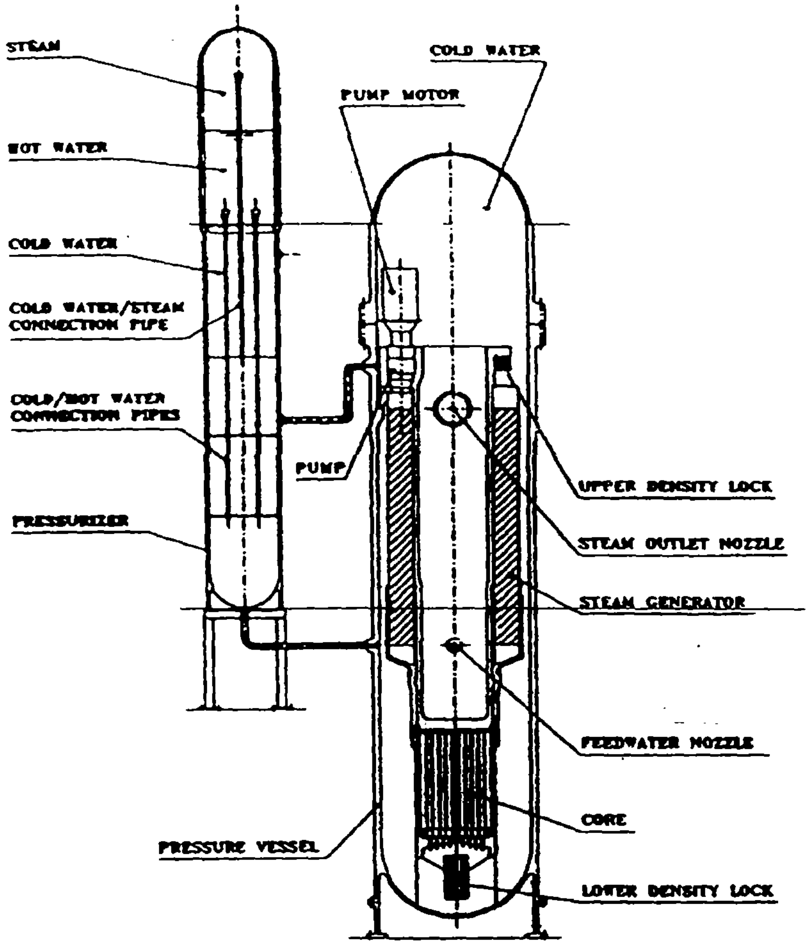

Figure 2 ISIS Components Arrangement

Outstanding feature is the complete immersion of the Pressure Boundary, made up, for each module, of a Reactor Vessel and of a separated Pressurizer with interconnecting Pipe Ducts, in a large pool of cold water.

During normal operation, the heat generated in the core is transferred to the SGU via the water circulated by the Primary Pumps, which are located at the top of the Inner Vessel. In case of unavailability of this heat transfer route, the cold and highly borated water of the Intermediate Plenum enters the Primary Circuit from the bottom, mixes up with the hot primary water, shuts down the reactor and cools the core in natural circulation. The same process, by heating the intermediate plenum water and the Pressure Boundary metal, activates the natural heat transfer route towards the Reactor Pool, which contains approximately 6.000 cubic meters of cold water.

The water inventory in the Reactor Pool is large enough to allow the water itself to remain below the boiling point after removal of the decay heat for about a week.

Cooling down of the plant pool is guaranteed, anyway, for an unlimited time, by two loops provided with water-air heat exchangers in natural circulation, sized to reject to the atmosphere, at steady state, approximately 2 MW and thereby capable to prevent the pool water from boiling.

Similarly to the PIUS reactor concept, the shut down and cooling functions of the core are carried out, in any condition, by the highly borated cold water of a plenum, which is hydraulically connected to the primary system by means of density locks.

However, unlike the PIUS, the intermediate plenum of ISIS contains a relatively small inventory of cold water (approximately 300 cubic meters per reactor module) at primary system pressure.
The description of the main characteristics of the major reactor components can be found in [1].

3. Main Control Systems Philosophy

The operation of ISIS reactor is based on the balance of three pressure heads:

1. the elevation heads provided by the cold water in the inner vessel pool between the upper and the lower density locks
2. the elevation heads provided by core and riser with the associated pressure drops.
3. the pressure heads deriving from the balance of head provided by the primary pumps minus the pressure drops in the steam generator and downcomer

Those three pressure heads must be continuously balanced by the control system in order to assure proper reactor operating conditions; if the pressure heads provided by the primary pumps, for example, decreases, some cold borated water will enter the primary system thorough the lower density lock, and on the contrary if the pressure heads provided by the primary pump increases some hot water will leave the primary system through the lower density lock.

In this context, the basic control philosophy that has been identified, is to operate the reactor maintaining constant the core outlet temperature, at any power level (in the range of interest of control); this is done with the purpose to minimize the actions requested to the primary pumps which have to compensate all the temperature change in the riser. Since the plant is not provided with control rods and the steam generator has quite a low heat capacity, the fastest way to introduce or extract reactivity from the core is to change the average moderator temperature by acting on the steam generator feedwater flow. It means that a power change request is transmitted to the feedwater control system that firstly changes the feedwater flow and consequently the core inlet temperature and the reactor power changes according to the feedwater flow variation.

The core outlet temperature tends to remain almost unchanged by itself, but any deviation from the design value is adjusted by inserting or extracting Boron from the core, in order to match the reactivity balance and to report the average core temperature at the programmed value. The steam flow is changed by the steam pressure control system that acts on steam flow control valves to maintain the steam line pressure even when feedwater flow variations occur.

Temperature variations of primary system causes some water to enter or leave the primary system through the two density locks. The lower density lock control acts in such a way (changing the primary pumps rotational speed) to avoid any flow through the lower density lock as well as the upper density lock control system acts in such a way (injecting or extracting flow in the riser) to avoid any flow through the upper density lock.

Fig. 3 shows the location, in terms of sensors and actuators, of the mentioned control systems, i.e.:

- Feedwater and Reactivity Control System (FRC);
- Primary Pressure Control System (PPC);
- Secondary pressure Control System (SPC);
- Lower Density Lock Control System (LDC);
- Upper Density Lock Control system (UDC);
- Boron reactivity Control system (BRC).

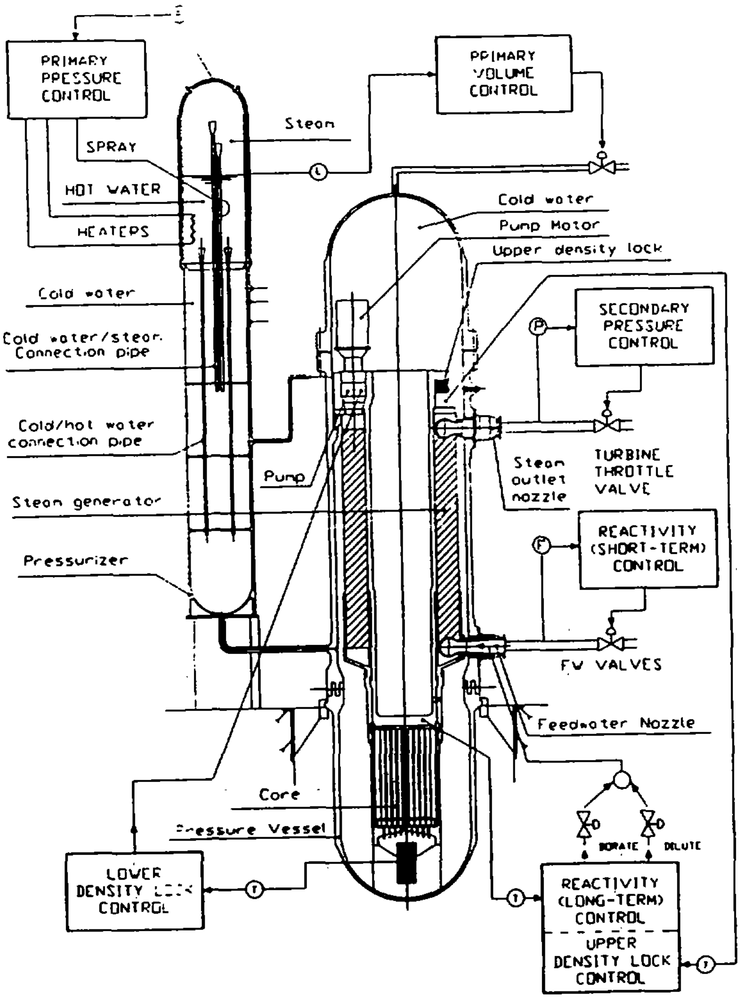

Figure 3 - ISIS Reactor with the main controls

In particular, the LDC system performs the task to maintain constant the hot/cold interface position (known by measuring a set of water temperatures in the pipes of the lower density lock itself: the interface is maintained at a temperature which is the average between the intermediate pool temperature and the core inlet temperature). The variation of the temperature in the middle of the density lock, with respect to the above defined variable set-point, acts on the primary pumps rotational speed, varying the primary flow and, finally, readjusting the hot/cold interface.

Similarly, the UDC system controls the hot/cold interface location in the upper density lock, maintaining the mean section of the density lock at a constant temperature, intermediate between the riser and the intermediate pool temperature. The aim is to avoid inlet of borated water to the primary system and to control the primary system inventory, by injecting or extracting water from the primary system through a control valve.

It is to be noted that the control schemes proposed , as a first approach, are quite "classical", being formed by P-I Controllers, Lag filters, non-linear elements like deadbands, etc.

4. Results of simulation of manoeuvres

After the first functional definition of the control loops, their identification in terms of transfer functions and their individual basic assessment by means of a quite complete ISIS reactor model, built using the RELAP5/Mod3 computer program [5], the same non-linear model has been utilised to simulate typical load-following transients, which allow a significative validation of the overall control scheme and of the integrated control loops behaviour.

4.1 Step-wise power manoeuvre 100-90-100% of nominal power

In Fig. 4 the requested power and the turbine power are plotted; the latter matches exactly the set-point within about 3 minutes from the step request.

The FRC system operates in such a way to increase or reduce the power exchanged in the Steam Generator (S/G), and the SPC system varies the steam flow to maintain a constant pressure at the S/G outlet. The results of these actions are illustrated in Fig.5: feedwater flow and steam flow (controlling parameters) move as the power.

In Fig. 6 the core inlet and riser temperature are shown: the second is almost constant and the BRS is not activated; the core inlet temperature firstly increases, due to the feedwater decreasing, introducing negative reactivity in the core, then decreases, as the feedwater increases, to introduce positive reactivity in the core.

Pressuriser pressure and level show limited variations and, being controlled in a similar way as a typical PWR does, are not illustrated. More interesting is the behaviour of the flow through the two density locks (lower and upper). The first is shown in Fig. 7 and remains a very stable, due to the suitable variations of primary pumps rotational speed (Fig. 8), which is consistent with the behaviour of primary system temperatures. The second (Fig. 9) shows, instead, some oscillations, such to cause some borated water to enter the primary system (this fact causes the mismatch that can be noted between the initial and final, steady-state, value of many parameters (temperatures and main pumps speed). An optimisation of the UDC system logic should be performed to better cope with this step transient.

4.2 Power ramp 100-50-100% of nominal power

The power ramp variation at the rate of 5%/minute is suitably performed (see Figures 10 and 11). The control systems act as in the previous transient, but, being larger the power span to be covered, also the BRC system is requested to operate, actuated by the riser temperature variations outside a fixed deadband (Fig. 12); the core inlet temperature varies, as before, according to FRC system action. The resulting core boron concentration is illustrated in Fig.13: the system is activated for boration and deboration.

Also during this transient, the lower density lock presents a very stable behaviour, while the upper one presents some oscillations in correspondance with primary system cooldown or heatup processes: this causes the unwanted inlet of some borated water into the primary system.

5. Conclusions

The results reported show that the control philosophy adopted for the ISIS Plant is adequate to perform typical plant manoeuvres in the range 100-50% of nominal power.

Specifically, it has been shown as the plant, even if not provided with reactor control rods, is able to perform power changes as fast as the larger common PWR reactors using feedback on reactivity provided by change of moderator temperature.

The lower density lock hot/cold interface location is controlled with a limited adjustment of the primary pumps rotational speed (less than 2%), such that the plant safety is not impaired.

Some further adjustment of control logics and parameters is required, in particular for UDC system, that the analyses have shown to be critical. Also the more typical pressuriser control (PPC) needs optimisations.

Recent analyses have confirmed that the defined control scheme is also suitable, with limited modifications, to cover plant conditions below 50% of nominal power. Also a complete plant startup from cold conditions has been simulated, showing satisfactory results and an overall required time of about 10 hours.

References

[1] Cinotti L. , Rizzo F.L. ,"The Inherently Safe Immersed System (ISIS) reactor", Nucl. Eng. Des. 1993 , Vol. 143, pp. 295-300

[2] Amato, U. Monasterolo, R. Monti, A. Orazi, "Response of the Inherently Safe Immersed System (ISIS) Reactor to Accident Conditions", Third International Seminar on SMNRs, New Delhi, August 26-28, 1991

[3] Amato, A. Orazi,"Advanced Safety Features in Conception of New Passive Reactors: the Inherently Safe Immersed System (ISIS) Reactor", IAEA Technical Committee Meeting on Thermoydhydraulic of Cooling Systems in Advanced Water Cooled Reactor, Villigen, Switzerland, 1993

[4] Amato, L. Cinotti, "Using prompt self-depressurization as a key feature to assure safety", International Conference on 'New Trends in Nuclear System Thermohydraulics', May 30th -June 2nd, 1994 -Pisa, Italy

[5] Carlson, K.E. Riemke,L.A. Rouhani,S.Z. Shumway,R.W. Weaver,W.L. "RELAP5/Mod3 Code Manual", Vol. I,II,III,IV NUREG/CR-5535 - EGG-2596, June 1990

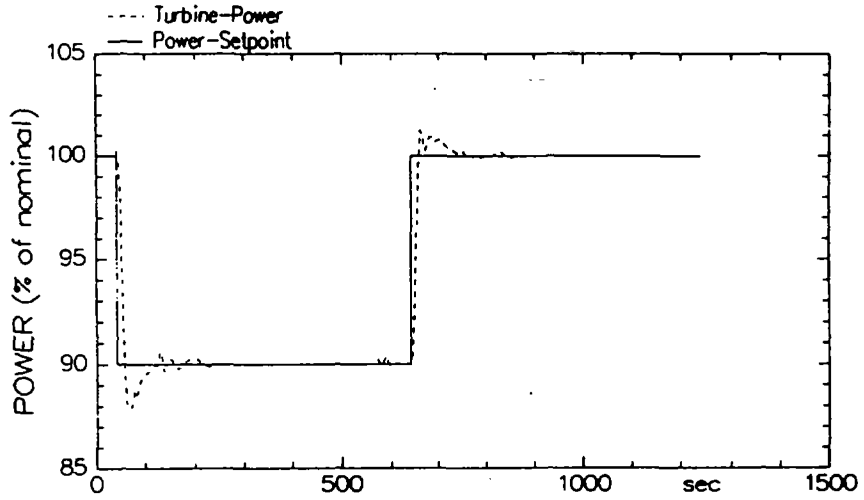

Figure - 4 Requested power and turbine power

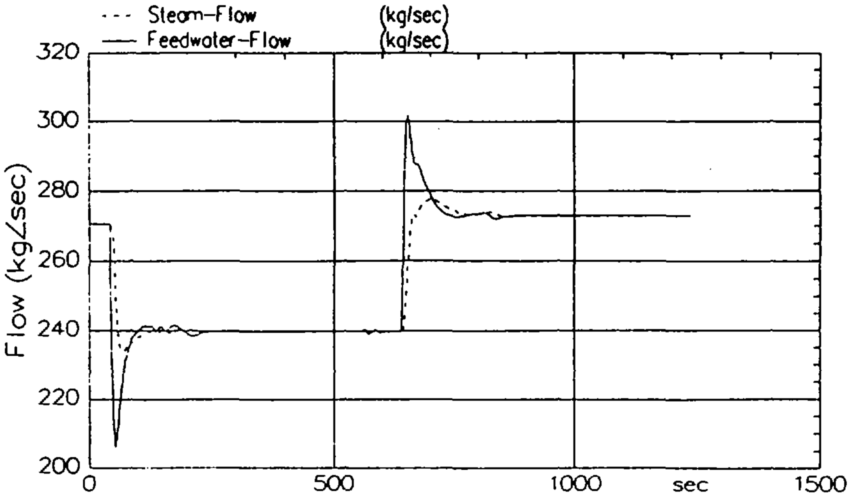

Figure - 5 Feedwater and Steam flow

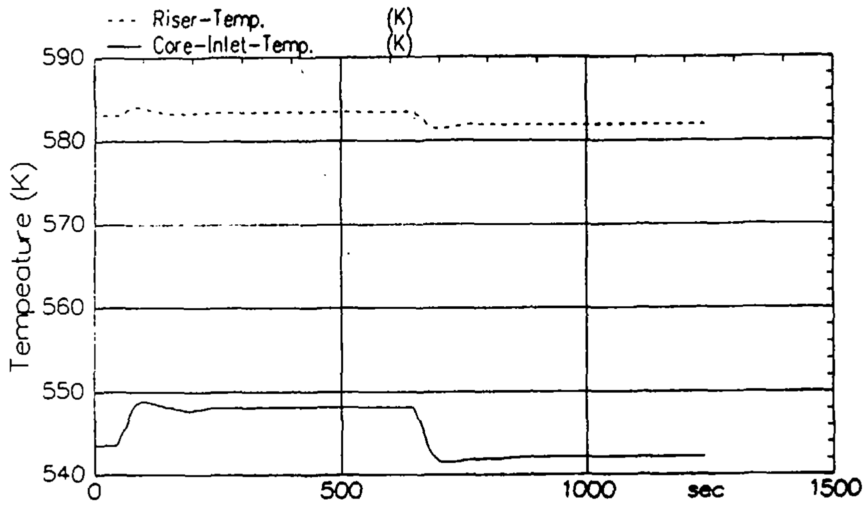

Figure - 6 Core Inlet and Riser Temperatures

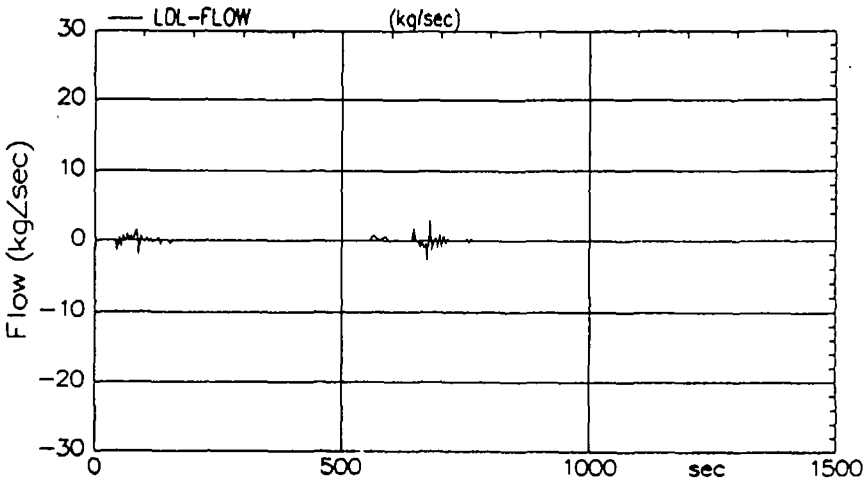

Figure - 7 Lower Density Lock Flow

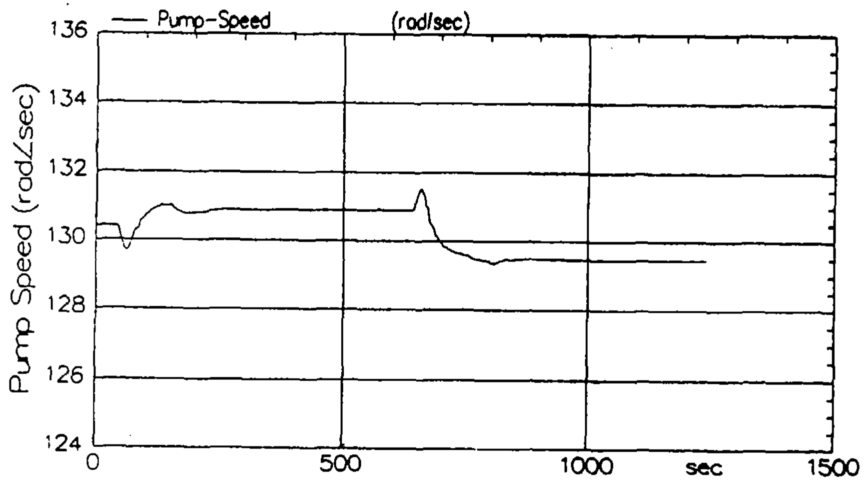

Figure - 8 Primary Pump Rotational Speed

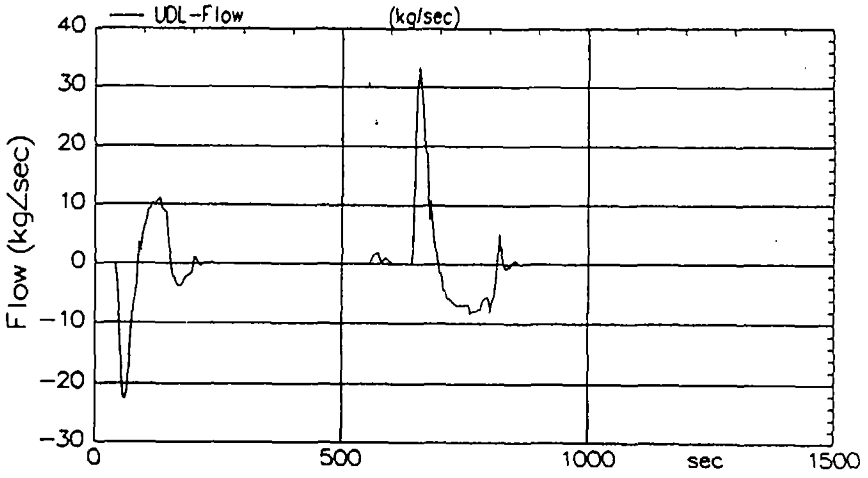

Figure -9 Upper Density Lock Flow

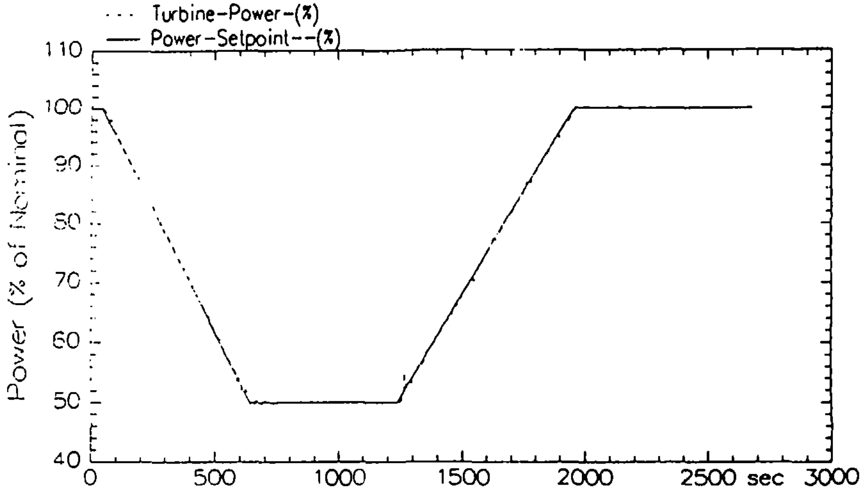

Figure - 10 Requested Power and Turbine Power

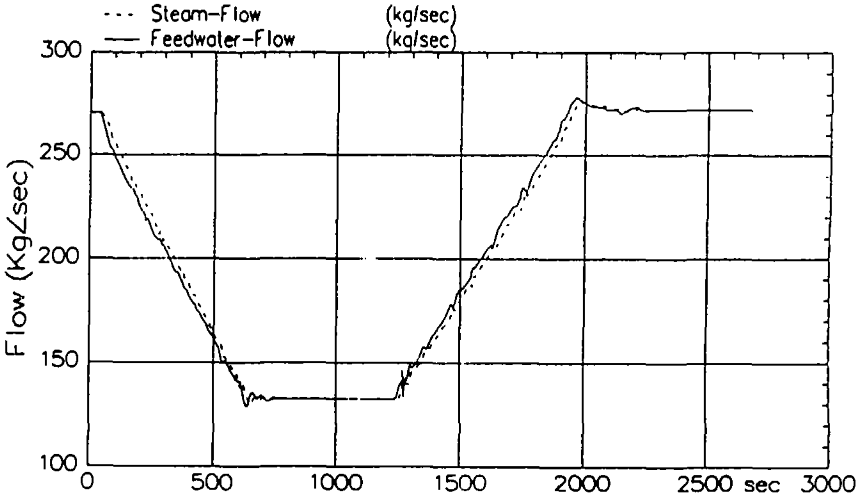

Figure - 11 Feedwater and Steam Flow

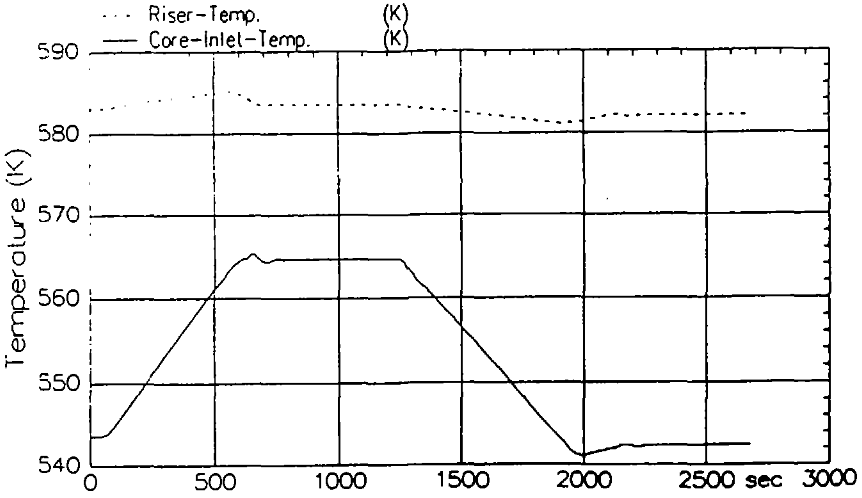

Figure - 12 Core Inlet and Riser Temperature

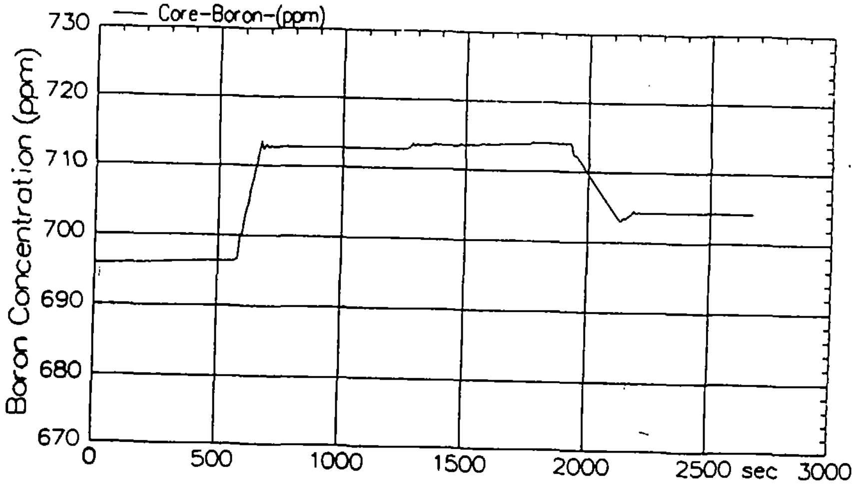

Figure - 9 Core Boron Concentration