बीएआरसी न्यूज़लेटर
BARC NEWSLETTER

PHYSICS DESIGN AND SAFETY ASSESSMENT OF 540 MWe PHWR

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The physics design work of 540 MWe reactor which started around 1984 and, training of the reactor physicists of NPCIL, were the responsibility of BARC. Over a long period of time, the Physics and Engineering design (by NPCIL) iterations of the core configuration, in-core physics, burnup optimisation, evaluation of reactivity devices, various incore monitoring algorithms, control and safety schemes, software and hardware of reactor regulation and protection systems, analysis of fuel management strategies and different computer code developments and their validation have been accomplished and the design was completed. Initially the core was designed for 500 MWe but subsequently, because of margins available in the MCP the reactor power could be increased to 540 MWe.

A number of computer codes were developed and/or evolved, to suit the requirements for design analysis and reactivity predictions of the 540 MWe PHWR. These are classified into the following five categories.

1. Computer codes for lattice calculations (CLUB)
2. Computer codes for Supercell Calculations of Reactivity Devices (BOXER).
3. Computer codes for Core Calculations (TRIVENI, TAQUIL and FEMINA)
4. Computer Codes for Simulation of Xenon Transient and RRS (TRIXEN).
5. Computer code for online flux mapping system and 3D-kinetics (3DFAST).

The calandria of the 540 MWe reactor, is a horizontal cylindrical vessel similar to 220 MWe PHWR, with its diameter being about 8 metres and length about 6 metres. Indian design of the reactor consists of 392 channels, whereas PICKERING –A (CANDU 500) design has only 390 channels. However, the safety and control system features were chosen to be similar to the then current design of CANDU 600. Moreover our reactor was made symmetric by addition of two more channels (H-01 & H-22) compared to Pickering.

In order to have better operating (bundle power) margins, the 37 rod cluster design was opted for as compared to the 28 rod cluster, used in CANDU 500, However, it cost a burnup loss of about 500 MWD/Te. Moreover, the choice of 37 rod cluster, which provides more margin on account of linear heat ratings, would help to raise the reactor power, without changing the cluster design. In addition to this due to non-boiling option of the coolant with 37 rod clusters, the PHT pressure increase, resulted in slightly thicker pressure tube (wall thickness of 4.5 mm as compared to 4.34 mm in CANDU 600), leading to an additional burnup loss of 180 MWD/Te.

Lattice Calculations

The lattice calculations for these advanced cluster designs was started, with the indigenously developed state-of-the-art code CLUB, based on multigroup integral transport theory. The computer code CLUB was a unique code which is treated cluster geometry exactly with multigroup cross section libraries. It was based on a combination of small-scale collision probability and large-scale interface current technique. This judicious combination yielded a computationally very efficient and an accurate method.

The computer code CLUB made use of the available WIMS 69-group cross section library. As the computer memory and the time required were both very large with the earlier computers, the 69-group cross section library was condensed to 27/28 group library, using a typical spectrum of a PHWR. Most of the lattice calculations were initially performed using the condensed version of the 27-group WIMS library. With the availability of more efficient computers in the 90's, the calculations were made using 69-group library. Later on, more cross section libraries were obtained from IAEA, under the WIMS Library Update Project. These cross section libraries contained 69 or 172 neutron energy groups and were generated from ENDF/BVI.8, JENDL3.2 and JEF-2.2 point data. There is one more library called IAEA library, which is obtained by taking the most recommended data for various isotopes from various point data sets. The computer code CLUB was modified to consider various new libraries obtained from the IAEA. The library generated from ENDF/BVI.8 point data has now been used, for lattice calculations of TAPS-3/4.

A large number of experiments were performed with 7, 19 and 28-rod fuel clusters and different coolants. Only one experiment has been performed with a 37-rod fuel cluster. These experiments were analyzed with the computer code CLUB and the results were generally found to be very encouraging. BARC participated in the IAEA's co-ordinated research program on "In-core Fuel Management Benchmarks for PHWRs" where the results of lattice calculations for 37-rod fuel cluster calculated with CLUB were compared with other international codes. The results of initial criticality obtained during startup of new reactors were also found to be extremely satisfactory.

Control System

For reactor regulation and control, different reactivity devices were provided. There are 17 adjuster rods (ARs) normally kept fully in, during operation and their purpose is to provide positive reactivity, whenever it is required. There are 14 zone control units (ZCUs) with partially filled with water with a capability to provide positive reactivity as well as negative reactivity to control the spatial flux distribution. Normally, the water level in the ZCU is maintained at about 45 % full level (FL). There are four control rods (CRs) normally kept out of the core, which are capable of providing negative reactivity, during operation.

Adjuster Rods

Adjuster rods are kept fully in during normal operation, could be withdrawn in banks (total 21 rods grouped in 8 banks) to add total positive reactivity of about 16 mk (12 mk for half an hour xenon over-ride and 4 mk for compensation of reactivity due to non availability of fuelling machine for about 10 days). On reassessment, it was concluded that, full recovery from a trip (Xenon override from 100%FP) need not be a basis for AR reactivity requirement. Instead, step back for different scenarios was considered from 100% FP to 65% FP and xenon over-ride requirement was worked out to be 8 mk. Thus it was decided to remove 4 out of the 21 ARs. As a result, a new banking scheme for 17 AR's with 8 banks was worked out, which maintains the symmetry of power distribution. Moreover, the location of these rods was chosen to achieve better flux flattening and power distribution.

The ARs do a flux flattening role in this reactor, unlike those in 220 MWe reactors, even though their worth is nearly the same. In 220 MWe thick shells (6 cm OD and WT 1.6 cm) are employed, while in 540 MWe they are thin (7.34 cm OD and WT 1.6 cm) and distributed in three planes, in the center of the core, achieving sufficient flux flattening.

Zone Control Units (ZCUs)

A distributed zone power control is vital for power distribution stability, since this neutronically large sized reactor, is unstable against xenon-induced power oscillations, in the azimuthal and axial directions. The first two higher modes do not have a large eigenvalue separation from the fundamental mode, the eigenvalue of the first azimuthal mode and first axial mode is 15 mk and 22 mk less than the fundamental mode, respectively. Thus seven radial zones each in two axial planes are provided for spatial control. The bulk power as well as power tilt control are performed by fourteen Zone Control Compartments (ZCC) by changing the level of partially filled light water. These ZCCs have been designed to provide ±3.5 mk. The location and length of each ZCC was optimized to achieve efficient and effective control. The response of the reactor to the action of various reactivity control devices, was studied in detail and corresponding S-curves were generated. As a result of this analysis, the location and size of some of the zone controllers were changed to meet control requirements.

Control Rods

The four control rods are always kept out and can be dropped or driven, in for step back or set back respectively, into the core, giving about 10 mk of negative reactivity to compensate for power co-efficient. In indian reactors, their positions have been shifted as compared to CANDU 600 and are located near ZCUs to increase their worth. These four rods are grouped in to two banks.

Shut Down System

As per PHWR safety philosophy, there are two independent shut down systems. The independence aimed are material and geometry of devices, direction and principle of actuation, initiating systems and even hardware and software of the electronics units. This safety philosophy was demonstrated and successfully implemented in 220 MWe PHWRs like NAPS and KAPS. There are two shut down systems (SDS 1 & SDS 2). In 540 MWe reactors these satisfy the safety requirements.

SDS 1

This system has 28 SRs made of SS-Cd-SS shells, which fall under gravity with spring to provide initial acceleration. They give about 72 mk when all the 28 rods actuate. However, for safety analysis, two maximum worth rods are assumed to be not available. Thus with 26 SRs, the worth comes out to be 52 mk. In the indigenous design, position of four rods has been shifted compared to CANDU 600, to improve the total worth.

SDS 2

This system consists of six poison nozzles in the horizontal direction (west to east) through which gadolinium nitrate is injected at high pressure, directly into the moderator. The initial rate of addition is aimed to be similar to the worth of SDS 1 (72 mk) as the total worth of the system works out to be about 300 mk.

Spatial Xenon Control

Xenon spatial oscillation occurs at constant power, due to prompt positive and delayed negative xenon feedback with a period of oscillation of about a day. The problem was tackled both by direct simulation and linear stability analysis. It was found that, xenon stability depended strongly on the core configuration. For the linear stability analysis, an accurate modeling of the reactor core was used and growth factor of instabilities was calculated, for various core states and power. It was also found that only the first azimuthal mode was unstable leading to diverging oscillations, while the first axial mode was close-to-stable with converging oscillations at full power. Below 60% full power, all the higher modes were seen to be stable. The problem of the control of xenon stability by zone control system was also studied in detail, by direct time-domain simulations. And to test the effectiveness and accuracy of the core flux control scheme and the simulation model, a benchmark problem was prepared under the IAEA CRP on core fuel management code packages. It was seen that the instabilities could easily be controlled, by using a simple proportional control algorithm.

Development of COPPS

The large core size has its implications on core safety too. The analysis of various Loss Of Reactivity Control (LORC) incidents showed that, distortions in flux could be highly localized and that the ex-core ion chambers may not be good representatives of reactor power. A reactor of this size needed a safety system such as a Regional Overpower (ROP) protection trip system, that could detect local overpowers. However, in 540 MWe design, partial boiling is not permitted. Hence the requirement of a complicated system like ROP was felt unnecessary and an equivalent simpler system, COPPS (Core Over Power Protection Stystem), was designed. The input to this system is obtained from cobalt SPNDs, strategically located in the core. Operating margins for the more frequently occurring flux shapes were maximized and a scheme for the calibration of SPNDs was worked out.

Instrumented Channels

To get the best estimation of reactor power, forty four instrumented channels distributed symmetrically in the core were identified where channel flow, channel in-let temperature and channel out-let temperatures were measured. The average thermal power is evaluated and fed to the COPPS system, to correct for the bulk power of the reactor.

Online Flux Mapping System

For flux mapping and monitoring the flux shapes in the reactor, 102 vanadium SPNDs have been used. These SPNDs are located in the form of an irregular grid in the core, based on the analysis of correlations between the change in local flux and change in the channel power for a large number of distorted flux shapes in comparison with the nominal flux shape. The detector signals have to be processed on-line, to obtain flux and power shapes in the entire reactor. The required software has been developed on a modal synthesis approach. Large amount of effort has gone into the generation of the fundamental and fifteen higher harmonics. Two different schemes have been developed for this purpose: one based on synthesising the 3D modes for nominal reactor configuration and second for obtaining them from 3D diffusion code, numerically, by an eigenvector elimination process. Once these basic modes are available, some perturbation modes depending upon the possible control RD configurations, estimated directly from 3D simulations and are directly added to the set. An online flux mapping algorithm, based on a least square method was developed and successfully implemented. Indigenously manufactured cobalt and vanadium SPNDs were loaded in the central thimble locations of KGS 1 & 2 and RAPS 3 & 4. Usage of these SPNDs in TAPS 3 & 4 was recommended after studying their performance.

Burnup Optimisation

All the reactivity devices are kept in or get inserted into the zircaloy guide tubes. These guide tubes are anchored to the bottom of the calandria vessel, by SS housing assemblies and employ inconel springs, to keep the guide tubes upright (about 1300 Kg of SS & 190 Kg of inconel). The initial physics optimisation study, carried out with two burnup zones with nominal position of the reactivity devices, (ZCC partially filled and AR's fully in) along with loads due to all the guide tubes, resulted in average exit burn up of about 6800 MWD/Te. The optimisation did not consider the loads due to detectors (SPNDs) and anchors of the guide tubes of reactivity devices in the bottom reflector. The subseqent reoptimisation after including loads due to the anchors of guide tubes revealed that bottom anchors affect the power distribution leading to a top-to-bottom tilt and load of these anchors was estimated to be about 1000 MWD/Te. This leads to the re-examination of the various reactivity requirements from the point of view of control as well as detector requirements. Also, the presence of seventeen adjusters in the core, produces a dip in the center. Therefore, analysis showed that the flux dip in the center due to adjusters and the top to bottom tilt can be corrected only if three burnup zones are considered. The burnup optimisation with three burnup zones resulted in average exit burn up of about 6900 MWD/Te.

Regulatory review

The Reactor Physics Design Division (RPDD) hired by AERB provided a complete regulatory review of TAPS 3 & 4 because of its expertise in the field,

In depth review of DBRs on Physics, Control and Instrumentation and PSAR was taken up and the suggestions made, were incorporated.

RPDD provided technical expertise to NPCIL, in preparing the document "Physics Design Manual" which included the lattice and core parametric studies using the latest IAEA cross-section library ENDF B-VI/6.8.

The different initial fuel loading configurations (which included usage of DU and DDU bundles) were studied and their follow-up till equilibrium is reached, was reviewed.

The experience of the RPDD was utilised in the design, safety review and commissioning of new systems like LZC, MLPAS and SDS 2.

The RPDD physicists played a lead role, in the safety review of the commissioning aspects of both TAPS 3 & 4 during the following activities

- Initial fuel loading
- Calandria filling – bulk addition of moderator (sufficiently poisoned)
- First approach to criticality
- Phase – B Commissioning
- Phase – C up to 50% FP and 90 % FP.

ANNOUNCEMENT

Forthcoming conference

DAE-BRNS Workshop on Physics and Astrophysics of Hadrons and Hadronic Matter

November 6 -11, 2006

Venue :
Visva Bharati University,
Shantiniketan

A series of workshops have been planned in the area of hadron physics, hadronic matter and its applications to astrophysical systems in order to provide a forum for discussion for researchers working in these fields. The general format of these workshops is (1) lecture series and (2) seminars. The present workshop is third in the series.

Recent developments in the following topics will be discussed:

1. Hadron Physics
2. Nuclear Effective Field Theory
3. Neutron Stars.

Participants can send their applications on plain paper or email giving name, institute and field of interest by August 30, 2006.

Ph.D. students may please send a recommendation letter from their supervisors. Young researchers are very much encouraged to participate, limited financial support towards travel may be available for them.

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