AERB SAFETY GUIDE NO. AERB/SG/D-7

CORE REACTIVITY CONTROL

IN

PRESSURISED HEAVY WATER REACTOR

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FOREWORD

Safety of public, occupational workers and the protection of environment should be assured while activities for economic and social progress are pursued. These activities include the establishment and utilisation of nuclear facilities and use of radioactive sources. They have to be carried out in accordance with relevant provisions in the Atomic Energy Act 1962 (33 of 1962).

Assuring high safety standards has been of prime importance since the inception of the nuclear power programme in the country. Recognising this aspect, the Government of India constituted the Atomic Energy Regulatory Board (AERB) in November 1983 vide standing order No. 4772 notified in Gazette of India dated 31.12.1983. The Board has been entrusted with the responsibility of laying down safety standards and to frame rules and regulations in respect of regulatory and safety functions envisaged under the Atomic Energy Act of 1962. Under its programme of developing safety codes and guides, AERB has issued four codes of practice covering the following topics:

Safety in Nuclear Power Plant Siting
Safety in Nuclear Power Plant Design
Safety in Nuclear Power Plant Operation
Quality Assurance for Safety in Nuclear Power Plants.

Safety guides are issued to describe and make available methods of implementing specific parts of the relevant codes of practice as acceptable to AERB. Methods and solutions other than those set out in the guides may be acceptable if they provide at least comparable assurance that nuclear power plants can be operated without undue risk to the health and safety of general public and plant personnel.

The codes and safety guides may be revised as and when necessary in the light of experience as well as relevant developments in the field. The annexure, foot-notes, references and bibliography are not to be considered integral part of the document. They are included to provide information that might be helpful to the user.

The emphasis in the codes and guides is on the protection of site personnel and public from undue radiological hazard. However, for aspects not covered in the codes and guides, applicable and acceptable national and international codes and standards shall be followed. Industrial safety shall be assured through good engineering practices and through compliance with the Factories Act 1948 as amended in 1987 and the Atomic Energy (Factories) Rules, 1996..

The Code of Practice on Design for Safety in Pressurised Heavy Water based NPPs states the minimum requirements to be met during the design of a land based thermal neutron reactor power plant in India for assuring safety. The safety principles and requirements for the core reactivity control are enunciated in this code. This safety guide elaborates these requirements and provides acceptable methods to achieve them.

The safety guide on core reactivity control has been prepared by the staff of AERB, BARC, IGCAR and NPC. This guide on the physics of the control and safety aspects of pressurised heavy water reactors is unique as it takes into account the Indian expertise in design and safety analysis. However, care has been taken to include important aspects from available international documents, a list of which is given in the references.

This safety guide has been reviewed by experts and vetted by the AERB Advisory Committees before issue. AERB wishes to thank all individuals and organisations who reviewed the draft and finalised this safety guide. The list of persons who have participated in the committee meetings, alongwith their affiliations, is included for information.

(P.Rama Rao)
Chairman, AERB

DEFINITIONS

(Definitions marked * are specific to this Guide)

Accident Conditions[1]

Substantial deviations from Operational States which are expected to be infrequent, and which could lead to release of unacceptable quantities of radioactive materials if the relevant items important to safety did not function as per design intent.

Anticipated Operational Occurrences[2]

All operational processes deviating from normal operation which may occur during the operating life of the plant and which in view of appropriate design provisions, neither cause any significant damage to Items Important to Safety nor lead to Accident Conditions.

Cold Shutdown*

Shutdown state of the reactor with fuel, coolant, and moderator at ambient temperature conditions.

Commissioning[3]

The process during which structures, systems and components of a facility, having been constructed, are made operational and verified to be in accordance with design specifications and to have met the performance criteria.

Criticality *

Criticality is a state of a system containing fissile nuclides in which a steady time independent expected neutron population can be maintained in the absence of a source, i.e.,$k_{eff}=1$

Emergency Situation

A situation which endangers or is likely to endanger safety of the NPP, the site personnel or the environment and the public.

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[1] A substantial deviation may be a major fuel failure, a loss of coolant accident (LOCA) etc. Examples of engineered safety features are: an emergency core cooling system and containment

[2] Examples of Anticipated Operational Occurrences are loss of normal electric power and faults such as turbine trip, malfunction of individual items of control equipment, loss of power to main coolant pump.

[3] The terms Siting, Construction, Commissioning, Operation and Decommissioning are used to delineate the five major stages of authorisation process. Several of the stages may coexist; for example, Construction and Commissioning, or Commissioning and Operation.

Equilibrium Core *

The condition of the core of an operating reactor in which the rate of charging and discharging of the fuel in the core, averaged over a sufficiently long period of time, reaches and remains close to a design value.

Fresh Core *

The condition of the core after initial loading, which contains all fresh bundles with zero burnup.

Fuel Bundle *

An assembly of fuel elements identified as a single unit.

Guaranteed Shutdown State (GSS) *

GSS is a specified shutdown state of the reactor with sufficiently large reactivity shutdown margin, established by the addition of liquid poison into moderator to provide positive assurance that an inadvertent increase in reactivity, by withdrawal of shut off rods, cannot lead to criticality.

Hot Shutdown *

Shutdown state of the reactor with coolant temperature (inlet to reactor) and pressure close to normal operating condition and the coolant circulating pump running.

Normal Operation

Operation of a plant or equipment within specified operational limits and conditions. In case of nuclear power plant this includes, start-up, power operation, shutting down, shutdown state, maintenance, testing and refuelling.

Operational States

The states defined under Normal Operation and Anticipated Operational Occurrences.

Poison (Neutron Poison) *

A substance having high neutron capture cross-section, reducing reactivity.

Postulated Initiating Events (PIE)

It is a hypothetical event that could lead to Anticipated Operational Occurrences and Accident Conditions, their credible failure effects and their credible combinations.[4]

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[4] The primary cause of PIEs may be credible equipment failures and operator errors both within and external to the NPP, Design Basis Natural Events and Design Basis External man-made Events. Specification of the PIE should be acceptable to AERB.

Process Systems

Nuclear and conventional systems required for operation as per the design intent.

Protection System

A part of Safety Critical System which encompasses all those electrical and mechanical devices and circuitry, from and including the sensors upto the input terminals of the safety actuation system and the safety support features involved in generating the signals associated with the safety tasks.

Quality Assurance (QA)

Planned and systematic actions necessary to provide adequate confidence that an item or a facility will perform satisfactorily in service as per design specifications.

Reactivity (ρ)*

A parameter, ρ, giving the deviation from the criticality of a nuclear chain reacting medium.

$$\rho = \frac{k_{eff} - 1}{k_{eff}}$$

where k_{eff} is the effective multiplication factor. Reactivity is expressed in terms of mk (10^{-3} k). Other units used are dollar, cent, inhour and pcm.

Reactor Regulating System (RRS) *

System that provides for automatic control of neutron flux and reactivity in the core and the thermal output of the reactor for an approved power range (between 10^{-7} – 110% FP).

Safety Critical System (Safety System)

Systems important to safety, provided to assure, under anticipated operational occurrences and accident conditions, the safe shutdown of the reactor (Shutdown System) and the heat removal from the core (Emergency Core Cooling System), and containment of any released radioactivity (Containment Isolation System).

Setback *

Controlled gradual reduction in reactor power effected by Reactor Regulating System in response to an identified abnormality in one or more plant process variables, until the conditions causing the setback is cleared or the preset limit for power rundown is reached.

Shutdown State*

State of the reactor when it is maintained subcritical with specified negative subcriticality margin.

Shutdown System *

Shutdown system is a safety critical system, the purpose of which is to shutdown the reactor.

Shutdown Margin *

Shutdown margin indicates the minimum specified sub-criticality of reactor that should be achieved under shutdown condition at any time during the operation from the most reactive state of the core or under postulated failure of a specified number of shutdown device of the highest reactivity worth(s) for the given shutdown system.

Stepback *

Stepback means a fast reduction in reactor power initiated by the RRS in response to an identified abnormality in one or more plant process variables to a preset lower power level.

Trip *

Actuation of a shutdown system to bring the reactor to shutdown state.

CONTENTS

1. INTRODUCTION

1.1 Purpose

The purpose of this Safety Guide is to provide guidelines for the design of core reactivity control provisions to ensure safe and controlled reactor operation under all conditions and safely shutdown the reactor from all operational states and postulated accident conditions. The safety principles and requirements for the core reactivity control are covered in [1]. This Safety Guide elaborates these requirements and provides acceptable methods to achieve them.

1.2 Scope

The Safety Guide covers the reactivity aspects involved in design of the reactivity control devices and control systems. It also covers the means of sensing the reactor power and other parameters that provide signals for control and information for operator action to maintain safety of Nuclear Power Plant (NPP).

This Guide is applicable to standard 220 MWe and 500 MWe Pressurised Heavy Water Reactors (PHWR) with natural uranium as fuel[1]. Brief descriptions of the typical features of these reactors are given in Annexure-I. The design guidelines given in this Guide are not fully applicable to earlier versions of Indian PHWRs such as RAPS and MAPS or any other Heavy Water Reactor design with different fuel.

This Guide does not address the aspects of criticality in fuel storage (fresh or spent), since these aspects are not applicable for natural uranium fuel. However, if any other type of fuel (slightly enriched uranium or mixed oxide fuel) is used, proper consideration should be given as specified in [2].

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[1] Depleted uranium or thorium fuel may be used in the initial core of the reactor for achieving flux flattening.

2. SAFETY DESIGN GOALS

A basic safety design intent shall be to achieve, as far as practicable, reactivity behaviour characteristics of the core, which are favourable to safety. The core and its control shall be so designed that, under no circumstances uncontrolled increase of power occurs. The control system worth and the insertion rates shall be sufficient to override reactivity changes including internal dynamic reactivity coefficients such as temperature reactivity coefficients etc. (refer Sec.4) during all operational states and accident conditions. Reactivity insertion rate shall be within permissible limits.

3. REACTIVITY CONTROL PROVISIONS

3.1 The reactivity of the reactor core is controlled by the following means.

(i) Movement of reactivity control devices - solid or liquid neutron absorbers in tubes
(ii) Addition/removal of poison into/from the moderator
(iii) Refuelling to compensate for the loss in reactivity due to fuel burnup.

3.1.1 The refuelling of the reactor is done by natural uranium oxide fuel. In case other fuel types are to be used, clear administrative measures should be available to differentiate between various types of fuel [2].

During refuelling, the maximum reactivity added should be within the capability of the Reactor Regulating System (ref. Sec.5.1.1) .

3.2 The reactivity control provisions are required for the following functions.

- Excess reactivity control
- Power and power distribution control
- Shutdown
- Start-up

For achieving the above functions, suitable parameters like neutron flux, coolant temperature should be measured and may be supplemented by on-line measurement of reactivity where feasible. Reactivity control should be automatic, with a provision for manual mode under specific circumstances as given in Sec.7.2.1.

3.2.1 Under equilibrium power operating conditions PHWR operates with a relatively small excess reactivity. On-power refuelling process introduces small changes in reactivity. In addition changes in temperatures of fuel, coolant and moderator result in small changes in reactivity (ref. Sec.4.1), which are inherent in PHWR. These reactivity changes should be compensated automatically.

3.2.2 During the initial stages of operation, large excess reactivity is present up to about 140 Full Power Days (FPD) due to the absence/slow build-up of unsaturated fission products. The excess reactivity is compensated by addition of poison in the moderator. The reactivity changes due to fuel burnup are slow during this stage and can be controlled manually. Addition/removal of poison in the moderator is done during this phase of operation to minimise the required worth of reactivity control devices.

3.2.3 The inherent reactivity coefficients and power distribution effects are covered in Chapter 4. Power and power distribution controls are achieved by an automatic control system referred to as Reactor Regulating System (RRS) and aspects related to RRS are covered in Chapter 5 of this Guide. Aspects related to reactor Shutdown System are covered in Chapter 6.

4. CORE REACTIVITY EFFECTS

4.1 Reactivity coefficients

The following reactivity coefficients depend on the temperatures of fuel, coolant and moderator, and are generally controlled by automatic action of control devices. The coefficients also depend on core loading pattern with natural uranium fuel. It is required that in the range of power operation, the combined effect of these coefficients should be negative, with increase in power. The typical values of reactivity coefficients are given in Annexure-I.

4.1.1 Fuel temperature coefficient

The change in fuel temperature affects the effective resonance absorption of neutrons. It is negative and prompt. Fuel temperature is the major component that changes from a hot standby condition to full power operating condition (with no boiling inside the channels) and hence is also the power coefficient.

4.1.2 Coolant temperature coefficient

This coefficient depends on the temperature of the coolant. It becomes less negative or slightly positive at higher temperatures (> 250°C). In pressure tube type reactor, this variation is masked by the simultaneous change in fuel temperature in the coolant channel (ref. Sec. 4.1.3).

4.1.3 Channel temperature coefficient/PHT temperature coefficient

In PHWR, during the transition from the cold to hot standby condition, the fuel and coolant temperature variations happening together *are* of importance and the two effects cannot be separated. The reactivity variation in this range is called the channel temperature coefficient.

4.1.4 Moderator temperature coefficient

The variation in the temperature of moderator in the operating range of a PHWR is very small (< 25°C). The reactivity variation due to changes in moderator temperature alone is also very small. It also depends on the boron present in the moderator. It is very nearly zero or slightly positive.

4.2 Reactivity effects of fission products

The fission products, which are formed in the fuel during fission process, are broadly categorised into unsaturated fission products and saturated fission products. Saturated fission products (xenon, samarium, rhodium etc.) have relatively very large absorption cross-section for thermal neutrons and they reach an equilibrium reactivity load within a few days of steady state of power operation. On the other hand, unsaturated fission products continue to build-up with fuel burnup because of low absorption cross-section for thermal neutrons. Reactivity effects of unsaturated fission products are taken care of by on-power refuelling whereas reactivity effects of saturated fission products are taken care of by manual and/or automatic action depending on the operating scenario.

4.2.1 Effects of xenon

Xenon concentrations are quite sensitive to flux/power levels. Any increase or decrease in power level will result in change in xenon distribution leading to flux/power tilts in the core. Due to prompt reactivity effects of xenon burnup and delayed reactivity effects of xenon production, power changes can result in power oscillations. In reactor upto about 220 MWe, these oscillations die out on their own while in 500 MWe PHWR, they could lead to sustained power swings. Such xenon induced power oscillations should be analysed for the potential modes of instabilities and automatic corrective measures should be provided to suppress the dominant modes.

4.2.2 Effects of power redistribution

Power redistribution affects generally the fuel temperature and xenon. In PHWRs beyond 220 MWe capacity, such redistribution leads to oscillations in xenon distribution and will lead to hot spots if not controlled quickly.

4.3 Reactivity effects of poison in moderator

In equilibrium condition, PHWR~~s~~ normally operate*s* without poison in the moderator. When the core contains excess reactivity (either in the initial core or in the absence of xenon) beyond the capability of control system, poisons such as boron or gadolinium should be added to the moderator during the operation. The reactivity change with respect to concentration depends on the initial poison concentration. Unintended dilution will add positive reactivity. The design should provide required features for preventing unintended removal of poison. This should be achieved by system engineering and/or clearly enunciated administrative control means to avoid unintended removal of poison.

Some of the reactivity effects mentioned in Sec. 4.1 are affected by the poison concentration in the moderator.

4.4 Neutron kinetics parameters

4.4.1 Delayed neutron fraction

Delayed neutron fraction in PHWR consists of two parts. First part is due to delayed neutrons produced within the fuel because of fission products and the second part is due to photoneutrons, which are produced by the absorption of gamma rays in heavy water. Due to longer half lives of photoneutron precursors, the PHWR transients are slower when power level changes. It is called 'delayed neutron hold back' effect.

4.4.2 Prompt neutron life time

Prompt neutron life time in PHWR~~s~~ is the largest among thermal reactors due to softer spectrum and lower absorption characteristics of the natural uranium core.

4.5 Reactivity effects of isotopic purity (IP) of heavy water

Variation of reactivity with moderator IP is large (of the order of 20 - 25 mk for 1 % change in IP). So, it is essential to specify a very high IP for moderator[5].

Due to relatively small volume of coolant inside the lattice cell, reactivity effect due to change in coolant IP is small (about 1 mk for 1% change in IP).

While a lower value of moderator IP puts a penalty on economics of operation, the lower values of coolant IP result in higher void reactivities, as explained in Sec. 4.6.

4.6 Coolant void coefficient

4.6.1 A unique feature of Natural Uranium fuelled_pressure tube type reactors is that the density reduction resulting from loss of coolant or coolant voiding leads to addition of positive reactivity. Since coolant and moderator are physically isolated, loss of coolant in a PHWR does not result in total loss of moderation as in Light Water Reactor.

The physical characteristics of PHWR, i.e. the low temperature heavy water moderator, the high temperature heavy water coolant, and the natural uranium fuel, lead to a positive coolant void coefficient. This results from a small shift in the neutron spectrum on coolant voiding, which affects the absorption rates in the thermal and epithermal range, and from loss of neutron scattering which affects the absorption rates at high energies. These result in the increase of all four factors involved in the effective multiplication factor.

4.6.2 There are two major types of LOCA to be considered. One which happens outside the core due to break of PHT lines, feeders, inlet/outlet header etc. and the other which happens inside the core due to simultaneous break of pressure tube and calandria tubes.

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[5] The nominal IP of moderator is 99.8 %; For achieving higher burnups, higher IPs are employed.

4.6.3 Out-of-core LOCA:

Depending on the size and location of the break as well as the temperature and pressure of PHT the blowdown rate could vary. These could be again divided into two: small LOCA and large LOCA. In a small LOCA the involved piping diameter is of the order of a feeder line or so (<5% of inlet header) which constitutes majority (nearly 99%) of total PHT system. From reactivity point of view the transients arising out of such failures are handled by the RRS itself. Mainly the reactor trips might get initiated from process parameters other than neutronics.

A large LOCA result*s* from breakage in headers or the large sized pipings between them. The maximum credible break would be the double-ended guillotine break of the inlet header. Certain medium sized breaks (25% - 40% of inlet header) may lead to flow blockages inside the core leading to severe temperature transients in the fuel. But reactivitywise they would be enveloped by the maximum credible break. In such cases the reactivity addition due to voiding could be very high (even upto about 10 mk/sec for short duration initially) and the reactor should be shutdown quickly. This transient dictates maximum negative reactivity addition rate requirement and actuation delays permissible for the SDS, such that the ECCS criterion is followed.

4.6.4 In-core LOCA:

The other type of LOCA happens inside the core due to the simultaneous break of pressure tube and calandria tube. Due to this PHT coolant gets inserted into moderator. In this case the probability for simultaneous failure of one or more PT+CT has to be evaluated. For one PT+CT failure the voiding rate would be slower. The main concern here is the dilution of poison in the moderator by the unpoisoned PHT coolant leading to the positive reactivity addition. The total PHT inventory and any other inventory of heavy water, which could be added to PHT, should be taken into account, coincident with the moderator containing the maximum allowable concentration of soluble neutron absorber ('poison'). The emergency coolant injection system containing light water should be assumed to be unavailable. The shutdown system worth should be such that it exceeds all the positive reactivity effects added together, plus the shutdown margin. This transient puts maximum requirement on the depth of SDS.

The scenario could be different depending on the coolant temperature and pressure. The cold high pressure scenario would lead to poison dilution resulting in large reactivity insertion. If PHT is hot it would lead to creation of large bubbles in the moderator system, thus reducing the slowing down properties of the moderator, which might introduce negative reactivities. All these scenarios have to be properly assessed to determine the worst case. If the Shutdown System or supplementary systems inject poison into the moderator the possibility of such poison bypassing the core due to moderator swelling and escaping via moderator pressure relief systems (OPRDs) should also be taken into account. Scenarios have to be worked out regarding “whipping” of the PT and CT damaging SDS guide tubes and impairing shutdown action especially for shutoff rod based SDS-1. The maximum no. of shutoff rod guide tubes that may get affected would have to be worked out.

Since this positive reactivity is unavoidable, safety features should be adequately engineered in such a way that the probability of LOCA without shutdown action, leading to extensive damage of the core, becomes insignificant. One such feature is the provision of two independent shutdown systems in the design, such that probability of LOCA without any shutdown action is insignificant. (refer Sec. 6.2.3 and 6.2.4)

4.6.5 LOCA reactivity increases with the reduction of isotopic purity (IP) of the coolant. During operation, the coolant may get downgraded.

Hence the void coefficient has to be evaluated for the minimum possible IP and maximum possible poison in the various core conditions during the life of the reactor and LOCA analysis should be done taking these into consideration. The safety aspect arising out of positive void coefficient of reactivity should be addressed in detail in the safety reports.

In current designs of 220 MWe PHWR with a single "figure of eight" loop of coolant circulation any break in the PHT circuit results in complete voiding of the core.

In 500 MWe PHWR, the PHT circulates in two separate "figure of eight" loops, with each loop serving one half of the core i.e., one half of the channels. The two loops have to be engineered such that both do not void simultaneously.

5. REACTOR REGULATING SYSTEM (RRS)

The role of RRS is to control the neutron power and power distribution for a demanded thermal power within acceptable limits consistent with plant safety. RRS includes instrumentation, hardware, software and control devices.

RRS is vital for the normal operation of NPP and its failure during operation demands shutdown. Hence, RRS shall be designed with a high degree of reliability, adequate redundancy and of fail-safe design [3].

5.1 Reactor regulation

RRS should be designed for automatic operation in the specified range of power operation. All the reactivity devices under the control of RRS should operate automatically, with a definite provision for manual control, when necessary. In special circumstances like start up from low power, manual control of RRS devices is permitted. (refer Sec. 6).

5.2 Reactivity requirement for regulation

The reactivity devices, which are controlled by RRS, should have sufficient reactivity worth, both in depth and direction, for manoeuvrability of expected reactivity loads. The various reactivity changes are :

- fuel burnup (-ve)
- refuelling (+ve)
- limited xenon decay (+ve)
- xenon build-up (-ve)
- xenon burn-up (+ve)
- xenon induced power oscillations
- temperature coefficients of core components (ref.4.1)
- addition/removal of poison from moderator, etc.

Based on above, three different groups of reactivity devices are required, out of which one group shall be designed to add reactivity, second group shall be designed to subtract reactivity and the third group shall have the capability to either add or subtract reactivity.

Reactivity control devices, which are fully IN, fully OUT or partially IN respectively are provided under the control of RRS to meet the above requirement. From quick controllability and safety point of view, the second and third groups of reactivity devices should be on automatic control by RRS.

RRS should also have the capability to identify power swings and power peakings between various zones of the reactor due to xenon induced power oscillations and should have distributed detectors and reactivity devices to control such power swings.

Provisions should be made to keep reactivity devices in the operating range specified in the design.

5.3 Reactivity control devices

The worth of a reactivity control device and the reactivity rate shall not be unduly high compared to the control requirement of the core. The total depth of the reactivity shall be distributed in a number of devices:

(i) to ensure proper flux distribution;
(ii) to keep minimum reactivity in a single device to avoid large reactivity transients in case of loss of regulation; and
(iii) such that the out of sequence operation of any devices does not lead to unacceptable increase in the reactivity worth of a single device/group (due to mutual shadowing or interaction etc.).

The control of individual devices or group of devices shall be divided such that a single device failure does not lead to an unacceptable reactivity rate of change and net change in reactivity.

5.4 Reactivity insertion rates

RRS design should have the capability to override all the fast reactivity transients during the start-up, normal operation and power increase/ reduction to arrive at the required rates of reactivity.

The upper limit of positive reactivity addition rate[6] should be such that during an intended power increase, it does not lead to a reactor period trip. Further, operation under RRS shall, in no circumstances, lead to a reactivity increase which is beyond the capability of reactor Shutdown System. The variations in different process parameters in their operational ranges should also be considered in assessing the reactivity rates.

5.5 Control of global and regional power

RRS shall control both global as well as regional power. Considerations for

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[6] A typical value for natural uranium PHWR is about 0.3-mk/sec ramp for critical condition.

anticipated transients shall include all plant parameters affecting the local and global power.

The response characteristics of the system should be such that it minimises possible overshoots/undershoots or hunting during power manoeuvring.

Changes in the spatial power (regional power) caused by local reactivity changes due to refuelling, xenon oscillations and changes of the rod positions shall be considered.

The system shall have means to control the neutron flux to obtain the acceptable spatial distribution considering the limitations on bundle and channel power. The fuel design should establish the limits on bundle power [3].

5.6 Detection and measurement

5.6.1 Reactor power measurement

Adequate number of neutron flux measuring sensors should be provided to assess global reactor power. Also, in reactors, which are prone, to flux instabilities due to perturbations, provisions for regional flux measurements (incore monitors) should be made. A proper assessment of the sensors to different radiations in the reactor core environment (neutron, gamma etc.) should be made. Irradiation effects (both prompt and delayed) on the detector response should also be ascertained.

5.6.2 Global power

The range of measurement for global power shall extend beyond the normal operational range by a reasonable margin. The upper end of the measurement should extend above the maximum power level, where the provision for reactor trip is envisaged. The lower power end shall extend up to the source power level expected after a reasonable duration of shut down. Typically, in PHWR, the measurement range selected is 10^{-7} to 1.5 full power. For power levels below 10^{-7} full power (ref. Sec.7.2.1).

If a single type of detector does not cover the full range, different types of the detectors could be used with at least one decade overlap. The design shall make provision for smooth changeover from one detector to another.

Provisions shall be provided for establishing correlation of neutron flux with the reactor thermal power, with adequate overlap of their ranges.

5.6.3 Regional power

In addition to measurement of global reactor power, there shall be instrumentation to allow estimation and control of regional power. Measurement or inference of channel power also should be provided.

5.6.4 Location and housing of detectors

The sensors shall be so located that they give proper signals to infer the reactor power in different power ranges. The location shall ensure minimum effect due to the variation in the position of the reactivity devices or boron concentration in the moderator. Where it is known that such effects could be present, adequate means to compensate for these effects shall be provided. For the location of the detectors, all operational states should be considered.

For devices located outside the reactor core, the influences of the local environment and the effects of possible flux tilts inside the core should be assessed. Also the effects of degradation of the detector housing leading to ingress of vault water should be avoided.

The structures and the guide tubes containing the detectors inside the core and in proximity to the core shall be designed so that the detectors can be located with required accuracy and do not get moved from their location due to equipment strain, moderator recirculation etc., during normal operation and the accident conditions.

The effects of changes in sensitivity of the incore detectors due to irradiation effects should be assessed on a continual basis and appropriate corrections to their signals for loss of sensitivity and constant background from daughter products should be made. In-situ calibration of the detectors should be periodically tested. The design shall facilitate replacement of detectors, when necessary.

6. SHUTDOWN SYSTEM

6.1 Purpose of shutdown system

The purpose of Shutdown System is to safely shutdown the reactor and maintain it in the safe shutdown state from all operational states and, during and after postulated accident conditions. The rate of addition of negative reactivity, the actuation delay and the effectiveness should be such that the shutdown action reduces the potential for fuel damage and consequent release of radioactive materials from reactor fuel [3]. The Shutdown Systems and their protection logics shall be independent of the RRS or other process control systems.

6.2 Means of shutdown systems

6.2.1 As required by the Design Code [1] , the means of shutting down the reactor, from operating and accident conditions, shall consist of two diverse systems each being able to perform its function meeting the single failure criterion. Each of the systems, on its own, shall be capable of quickly making and holding the reactor subcritical indefinitely by an adequate margin or alternatively, for a period long enough to permit the Shutdown System to be supplemented reliably, by another slower system.

The required reactivity worth of each Shutdown System should be based on an in-core LOCA, assuming simultaneous rupture of both the pressure tube and its associated calandria tube. The total PHT inventory and any other inventory of heavy water, which could be added to PHT, should be taken into account, coincident with the moderator containing the maximum allowable concentration of soluble neutron absorber (poison). The emergency coolant injection system containing light water should be assumed to be unavailable. The Shutdown System worth should be such that it exceeds all the positive reactivity effects added together, plus the shutdown margin, to be maintained from the time of completion of shutdown action.

In Shutdown System based on absorber rods/poison tubes, the individual average worth of each rod/tube should not be large[7], so that flux shadowing effects between devices are as small as possible and the single failure in actuation does not result in a significant reduction in reactivity depth.

6.2.2 The safety analysis should show that the simultaneous action of both Shutdown Systems is not required to prevent the consequences of any failures from exceeding the prescribed dose limits. Therefore, for events requiring a prompt shutdown of the reactor, the analysis should be done crediting each Shutdown System separately and considering single failure criterion in each system. Further, safety analysis should consider the reduction in SDKs worth resulting from adverse flux tilts due to:

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[7] In current PHWRs, the average worth of a single rod is kept within 2 to 3 mk.

(i) RRS malfunction,
(ii) LOCA
(iii) Refuelling pattern, etc.

6.2.3 The independence of two Shutdown Systems should be realised by adopting the principles enunciated in [3].

6.2.4 Analysis should demonstrate that there are no functional cross links between the RRS and the SDS, or between the two SDS.

6.3 Rate of shutdown

6.3.1 The rate of shutdown for each of the systems shall be adequate to render the reactor sufficiently subcritical in time to prevent fuel limits [3] being exceeded and to maintain the pressure boundary integrity in all Anticipated Operational Occurrences. For accident conditions, rate should be such that fuel and core damage is kept to a minimum.

6.3.2 The rate of shutdown is dependent on the following.

- Ability of the instrumentation to detect and respond to the need for a reactor shutdown. This requires a choice of instrumentation to adequately cover the range of PIE [3].

- Response time of actuation mechanism of Shutdown System. This may govern the choice of mechanism, though the response times are usually short.

- Location of the shutdown devices

The rate is sensitive to,

- the distance of the shutdown devices from the core prior to insertion. (The distance may be chosen so that the delay in effectiveness is minimum while integrity of Shutdown Systems is not jeopardised during the reactor life due to irradiation, temperature effects etc.)
- the location of absorber injection nozzles which should be such that the absorber may be quickly dispersed in the active region of the core.
- ease of entry of the shutdown devices into the core.
- insertion speed of the shutdown devices, like, gravity assisted drop of shutdown devices into the core accelerated by a spring used to provide the required speed, or hydraulic or pneumatic pressure injection of soluble absorber.

The rate of shutdown should take into account the maximum positive reactivity addition rate during any postulated accident.

6.3.3 The rate of withdrawal of shutdown devices shall be limited. The rate of positive reactivity addition during withdrawal should be such that it should not lead to a period trip. Start-up procedures shall ensure that reactor does not go critical when the shutdown devices are withdrawn after a reactor trip (ref. Sec.7.2).

6.4 Shutdown margin

6.4.1 The design shall ensure the capability of Shutdown System to render and hold the reactor subcritical by an adequate reactivity margin even in the most reactive core condition. This shall hold for the whole range of operating conditions and core configurations, and for Anticipated Operational Occurrences and accident conditions.

6.4.2 The minimum specified value of sub-criticality is called the shutdown margin[8]. The shutdown margin provided in the design should take into account the calculational uncertainties.

6.4.3 This shutdown margin should be demonstrated by analysis for all operational and accident conditions as per the Section 6.2. (Reactivity worths of Shutdown System).

6.4.4 Whenever reactor is shutdown (either due to a trip parameter or manually), the Shutdown System adds negative reactivity bringing down the power. Various positive and negative reactivity loads, which appear during the power reduction should be considered to get the net negative reactivity. The positive reactivity loads are typically due to power co-efficient, coolant temperatures or decay of xenon in certain situations, etc. The negative reactivities may be due to xenon build-up after shutdown. Further, positive reactivity introduced by any PIE should also be considered.

6.4.5 The various reactivity loads depend on burnup conditions of the core (initial, plutonium peak and equilibrium), boron in the moderator, isotopic purity and temperature of moderator and coolant.

6.4.6 The negative reactivity introduced by the Shutdown System should take into account:

- the effects of a given PIE on the Shutdown System devices
- conformity with the single failure criterion as per Code requirements[9].

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[8] Currently, a shutdown margin of 10 mk is being followed in Indian PHWR.

[9] Generally, the design caters to the non-availability of one or more devices of shutdown system of highest reactivity worth (for example, one shutoff rod of Primary Shutdown System/SDS-1 or one bank or nozzle of Secondary Shutdown System/SDS-2). When power operation is permitted with one shut off rod not available, then shutdown margin should be demonstrated with the non-availability of the next highest worth rod.

6.4.7 Generally, the negative reactivities inserted by the regulating devices are not to be considered in arriving at net subcriticality margin, unless their control logic is such that they introduce negative reactivity automatically under conditions requiring shutdown and the regulating devices possess independence and reliability which are equivalent to that of reactor protection system devices.

6.4.8 The absolute value of net negative reactivity should be greater than or equal to a specified shutdown margin from the time of completion of shut down action until restart operations are initiated.

6.4.9 The worths of various devices and reactivity loads should be estimated such that uncertainties associated with the calculations are taken into account conservatively. These assured worths may be estimated from comparison of calculations with measurements made in experimental and prototype reactors, and during reactor commissioning, and extrapolating to different states of the reactor during its life.

6.5 Shutdown states of the reactor

There are three shutdown states of the reactor as given below:

- Hot shutdown state
- Cold shutdown state
- Guaranteed shutdown state

6.5.1 Hot shutdown state

In this state, the reactor is shutdown from power operation and the coolant is close to hot standby condition. Positive reactivity effect due to power coefficient is overridden by Shutdown System in this state during normal shutdown.

6.5.2 Cold shutdown state

In this state, the reactor is shutdown from power operation and coolant and moderator are at room temperature. Power coefficient, reactivity arising out of cooldown of moderator and coolant, reactivity gain due to absence of saturated fission products (such as xenon) are the positive reactivities that need to be compensated in this state during normal shutdown.

6.5.3 Guaranteed shutdown state (GSS)

GSS is a specified subcritical state of the reactor with sufficient shutdown margin that provides positive assurance that an inadvertent increase in reactivity cannot lead to criticality. It is a highly subcritical cold shutdown state with a large amount of poison in the moderator where withdrawal of any reactivity device/system would not result in noticeable increase in neutron flux levels.

In a GSS, credit is not taken for the availability of Shutdown Systems. The subcriticality is achieved by adding sufficient amount of poison in the moderator, with poison removal system isolated. In such a sub-critical system, the safety Shutdown Systems as well as regulating systems can be safely disabled. The poison concentration is monitored at regular intervals during GSS. The amount of poison for GSS should be arrived at assuming the reactor core to be in the maximum reactive state with the following reactivity loads being absent with full core loading.

- Unsaturated fission products
- Fuel, coolant and moderator temperature
- Loads due to saturated fission products such as xenon, samarium etc.
- Adjuster loads
- No allowances for depleted thorium fuel bundles

The amount of poison required to counter all the loads mentioned above is estimated.

With this poison in the moderator, the reactivity arising out of the dilution of the poisoned moderator due to addition of unpoisoned coolant (nominal IP) and all available D_2O inventory (such as ECCS storage tank) connected to heat transport system should be estimated. To this reactivity value, LOCA reactivity for the estimated boron poison and specified shutdown margin should be added. The sum of all positive reactivities should be compensated by the addition of equivalent amount of poison in the moderator.

The accuracy in estimating the poison concentration should also be taken into account. The amount of poison thus arrived at should be ensured during GSS.

Addition or upgradation of moderator should not be done during GSS.

Transition from GSS to cold shutdown state should be done with adequate provisions for monitoring the neutron flux in the core.

6.6 Shutdown under blackout condition

The actuation devices of SDSs should be designed to be fail-safe under loss of power and should introduce negative reactivity into the system [3]. The shutdown reactivity requirement should assume cold state with absence of all saturated fission products like xenon etc. and should satisfy the shutdown margin at all times following blackout condition.

7. REACTOR START-UP

7.1 Initial start-up

In the initial start-up of the reactor, for fresh core, reactivity changes are under manual control, as RRS detection systems are not on scale. Hence, more sensitive start-up detectors should be used.

This phase of start-up consists of three typical tasks.

- Fuel loading and filling of PHT
- Filling of calandria with adequately poisoned heavy water moderator
- Approach to first criticality.

Approved procedures should be available for all the above tasks and the results should be fully documented in the commissioning reports including observations.

7.2 Normal criticalities

There are two modes for subsequent criticalities depending on the range of power as measured by ion chambers.

- Under RRS control
- Under manual control

The reactor should not become critical on withdrawal of shutdown devices. It should be ensured that reactor becomes critical only on withdrawal of regulating devices.

7.2.1 Under manual control

When the power level is below the minimum power level of operation of RRS, criticality is achieved by manually withdrawing the devices and/or removal of poison from moderator. For this purpose, manual mode of operation of the devices should be available. Monitoring of flux levels by incore and/or out-of core start-up detectors is necessary at all stages. Manual criticality should be done in a planned manner.

7.2.2 Under RRS control

After the reactor has seen reasonable period of operation, sufficient photoneutron sources are built keeping the RRS detectors on scale even after a shutdown. Therefore, reactor criticality can be achieved automatically under RRS control.

8. VALIDATION OF PHYSICS DESIGN AND ANALYSIS

In the design stage, it should be ensured that the neutronic databases, calculational models and computer codes employed in various stages of reactor simulation have been validated against computational benchmarks, available experimental measurements in zero power reactors and/or power reactors.

Suitable experiments shall be devised in the commissioning stages of each reactor operation to establish the reactivity worths of the devices, reactivity rates, response of RRS, the power run up and power run down rates, the accuracy of the signal levels and correlation between the various signals.

Reactivity worths of regulating devices and Shutdown Systems should be assessed experimentally (calibrated) in the 'as built' conditions of the reactor to collect and update the baseline design and operating information [2].

ANNEXURE-I

CORE PARAMETERS, REACTIVITY DEVICES AND FLUX MONITORING UNITS IN PRESSURISED HEAVY WATER REACTORS

Note : Typical values of the existing designs of PHWRs are tabulated below.
These should not be construed as the recommendations of the Safety Guide.

Parameter	220 MWe	500 MWe
No. fuel channels	306	392
Lattice pitch (cm)	22.86	28.6
Calandria		
Main shell OD (cm)	605	786
Core Length (cm)	500	594
Number of bundles (Inside Core)	10.1	12.0
Eqt.core(fuel region) radius (cm)	226	319
Reflector Thickness (main) (cm)	74	71
Extrapolated core length (cm)	508.5	600.0
Fuel Bundle and Lattice Data		
Bundle type (No. of elements)	19	37
No. of concentric rings	2 (1	6
Bundle length (cm)	49.53	49.53
UO_2 weight (kg)	15.3	21.6
U weight (kg)	13.4	19
Pressure Tube		
Material	Zircaloy-2/Zr-2.5% Nb	Zr-2.5% Nb
OD (cm)	9.1	11.2
Calandria Tube		
Material	Zircaloy-2	Zircaloy-4
OD (cm)	11.1	13.2
Gap		
Material (Annular Gas System)	CO_2	CO_2
Heavy Water Purity		
(weight% - Nominal values)		
Moderator	99.8	99.8
PHT	99.7	99.7

CORE THERMAL DATA

Total Fission Power (MWt)	802	1830
Total thermal power to coolant	756	1730
Maximum channel power-		
(Time - Average) MWt	3.06	5.5
Maximum Bundle Power-	430	642
(Time-Average) KWth		
$\int K d\theta$ (W/cm)	41	32.3
Av. fuel temperature (°C)	625	600
(assumed in physics calculations)		
Coolant Inlet temp. (°C)	249	260
Coolant Inlet pressure (kg/cm²)	99.5	116.0
Coolant Outlet temperature (°C)	293	304
Coolant Outlet pressure (kg/cm²)	87	101
Av.coolant temp. (°C)	271	282
PHT Inventory (t)	70	161.1
Mod. Average temp. (°C)	54.4	80
Mod. D_2O inventory in		
Calandria (t)	140	260

TYPICAL INFORMATION ON REACTIVITY DEVICES AND WORTHS

Purpose	RAPS/MAPS	NAPS/KAPS/KAIGA	500 MWe
1. Control and Regulation	Central adjusters	Regulating Rods	ZCC
	SS/Co	SS/Co	H_2O
	2 x 2	2 x 2	14
	4 mk	4 to 5 mk	7 mk
2. Xe Over-ride	Corner adjs.	Absorber Rods	Adjuster Rods
	SS/Co	SS/Co	SS
Number	4 x 2	4 x 2	17
	8 mk	8 mk	12 mk
3. Power	Central adjs.+	RR +	Control Rods
Reduction	Moderator level	Shim Rods	(SS-Cd-SS)
		2 x 2	4
		6 mk	11 mk
4. Shutdown	Moderator Dump	PSS (Rods)	SDS1-Shutoff Rods
		SS-Cd-SS	SS-Cd-SS
		14 Rods	28 Rods

		36 mk	72 mk
		SSS	SDS-2 (Liquid
		Lithium pentaborate	Poison-$GdNO_3$
		injection in tubes	injection in moderator
		12 tubes	6 nozzles
		32 mk	≈300 mk
5. Hold Down	Moderator Dump	ALPAS (8ppm Boron	
		Addition).	
		From KAIGA onwards	
		LPIS (8ppm Boron)	

TYPICAL INFORMATION ON FLUX MONITORING SYSTEMS

Purpose	NAPS/KAPS/KAIGA	500 MWe
Neutronic Detection		
1. Out of core	3 IC x 2 (NAPP)	3 IC x 3
	3 for RRS	3 for RRS
	3 for RPS	3 for SDS-1,3 for SDS-2
	3 IC x 3 (KAPP onwards)	
	3 for RRS, 3 for	
	PSS & 3 for SSS	
2. In-core	SPNDS in central	26 VFUs[102 V - OFMS
	Thimble NAPP-1	& 42 Co- ZCDs≤60 Co
	KAPP-2 (Passive)	COPPS(SDS-1]
		7 HFUs [≤48 Co (SDS-2)]
		(All are SPNDs)
Thermal Monitoring		
1. CTM (No. of	306	392
Channels)		
2. Instrumented	16	44
Channels		(40 physics + 4 PHT)

IC - Ion chamber
RRS- Reactor Regulation System
RPS- Reactor Protection System

REACTIVITY COEFFICIENTS

Parameter	220 MWe		500 MWe	
	Fresh	eqm	Fresh	eqm
1. Power coefficient	9.2 mk	4.8 mk	10 mk	3.2 mk
(Transition from				
power operation to				
hot standby)				
2. Reactivity gain	7.5 mk	1 mk	8 to 9 mk	-4 mk
due to transition				
from hot standby				
to cold S/D				
(channel temperature				
coefficient)				
3. Void reactivity coefficient				
(for 99.7% coolant IP)	11 mk*	7 mk	18 mk	
* with 7 ppm of boron in				
moderator				
Change in void coefficient				
per % change in IP	1 mk	1 mk		
Permitted coolant IP	98 %	97%(>100 FPD)		

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Dates of Working Group Meeting:

15 October 1992
24 July 1993
12 August 1993
01 September 1993
16 September 1993
27 October 1993
02 November 1993
11 November 1993
13 March 1996
17 April 1996
27 May 1996
18 June 1996
19 August 1996
06 December 1996
08 January 1997

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