Design modifications of Instrumentation & Control System of future FBRs based on feedback from safety review and commissioning experience

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Abstract: The purposes of Instrumentation and Control systems are to assist the operator in controlling the plant at the specified power level, monitor the plant and warn of deviations from normal conditions, prevent accidents by carrying out independent automatic safety and control actions, and mitigate consequences of an accident automatically. Design of I&C for PFBR is done in line with 'AERB Safety Criteria for design of fast reactors' and to suit operational and environmental conditions.

I & C of PFBR uses hybrid system consisting of computer based control system and hard wired system. Safety critical systems are built using triple redundant computer systems and / or hardwired systems. Safety related systems use dual redundant VME based real time computers and non safety class I & C systems are built using pre-developed systems.

For future FBR designs, thrust is given to align with Gen IV requirements and our experiences with safety review and commissioning also demands design enhancements. The core temperature monitoring probe is designed with three thermocouples for each fuel sub-assembly. Also the thermocouple channels will have indigenously developed hardware. Indigenisation has resulted in economic benefits. Triple redundant computer systems will have diverse computers running software developed by different agencies. The non-safety systems will use wireless interface for signal and command transfer.

Key Words

AERB **:** Atomic Energy Regulatory Board, CSR : Control & Safety Rod, DSR: Diverse Safety Rod

1. Introduction

The purposes of I&C systems are to:

- Assist the operator in controlling the plant in a manner consistent with specified power and safety targets;
- Monitor the plant and warn of deviations from normal;
- Prevent accidents by carrying out independent automatic safety actions and control actions;
- Mitigate consequences of an accident without operator intervention and then provide appropriate facilities for whatever action is necessary.

2. Design Criteria

Design of Instrumentation and Control systems are done as per the AERB Safety Criteria for design of fast reactors. In selection and implementation of I&C systems, the various operational requirements and environmental, seismic and safety classifications are considered and are qualified accordingly. Basic design principles of fail-safeness, single failure criteria, and provisions to prevent common cause failure, redundancy and diversity are considered and provisions are made suitably wherever required. Proven designs only used.

3. Power control and Power Setback

Manual control of reactor power is adopted with a provision of Power Setback. The magnitude of reactivity fluctuations due to burn-up is small and only few pcm is required to be compensated per day against burn-up loss, which needs raising of each CSR by fraction of a mm in each 8h shift. Power setback feature is provided to isolate the reactor from events originating from balance of plant or grid making use of the 60% dump capacity. To prevent incidents and accidents, the reactor is shutdown automatically when the set values of various parameters are exceeded. Plant is provided with CSRs and DSRs for this purpose. CSRs are used for power control as well as for shutdown, where as DSRs are used only for shutdown. Diverse instrumentation is provided to initiate shutdown of the plant in case of various design basis incidents. CSRs and DSRs are driven by independent instrumentation systems.

4. Control System Architecture

I&C systems are classified as Safety class-1, Safety class-2, and Non Nuclear-safety. The control system is a hybrid system consisting of hard wired and computer based systems. Processing of all safety class-1 parameters are hard wired except core temperature supervision wherein computers are used in view of the requirement for dynamic computation & processing. In house designed Computer based systems are generally used in SC-1, and SC-2 systems. Predeveloped systems are used in NNS systems. Three level control scheme is used: Field, Local Control Centre (LCC) and Control Room (CR) level. Components at the field level are sensors, Remote Terminal Units (RTU) and final control elements. LCC houses the signal processing electronics and components of computer based control systems. The RTUs in the field are in communication with the computers located in the LCC.

4.1.Control Rooms

Plant is operated from Main Control Room (MCR) in all states, for taking measures to maintain the plant in a safe state or to bring it back to a safe shutdown state after the onset of off-normal operational occurrences. MCR is provided with computer based display stations for providing information to the operator on plant parameters and for alarms. Safety parameters and other important parameters are provided with hardwired displays and alarm annunciators. Computers in LCCs and CR are connected through duel-redundant plant backbone.
Backup Control Room (BCR) is provided away from the MCR to shutdown and to maintain in the shutdown state when the MCR is inhabitable. Handling Control Room (HCR) is provided next to the MCR for operation of fuel handling machines. Local Control Panels are provided at the field level for auxiliary systems and infrequently operated systems.

5. Qualification of I&C systems

All the I&C system hardware are subjected to the qualification tests according to its safety and seismic classifications. Environmental, EMI/EMC and seismic tests are carried out to ensure that the I&C systems perform satisfactorily at all the anticipated environments.

5.1.Software Verification & Validation

I&C systems are verified and validated by Independent Verification & Validation committee based on the procedure standardised with the approval of AERB. The verification process provides supporting evidence that the software and its associated products

- Comply with requirements;
- Satisfy standards, practices, and conventions during life cycle processes; and
- Establish a basis for assessing the completion of each life cycle activity and for initiating other life cycle activities.

The validation process provides supporting evidence that the software meets software system requirements.

5.1.1.For Custom Built Systems (CBS)

For CBS, the design documents are submitted based on the safety classification of respective I&C system, by the designer/developer to the IV&V committee as and when required as the verification process progresses. During the process of IV&V, all the documents are reviewed for clarity, completeness, consistency, compliance to standards and traceability. Every verification step produces a report of the analysis performed, compliance of the outputs each phase with the inputs requirements, resolution of anomalies and the conclusions reached. The results of validation testing conducted as per the system validation procedure will also be documented and reviewed against the requirements detailed in the system requirements specification to confirm that the performance of the system meets those requirements. The objective of review is to establish that the software and hardware have been designed as per the recommendations of SG-D25. The review process is designed to confirm that the delivered system satisfies all its requirements and the safety analysis demonstrates safe behaviour of the system under all operational states.

5.1.2.For Pre-Developed Systems (PDS)

For PDS, the process for deployment involves mainly system manufacturing / procurement and integration, system configuration, application software customization and IV&V processes. In case of Certified-PDS, the systems would have been reviewed by some regulatory authority and have been used in nuclear power plants in applications of similar safety significance. In such cases, the committee will scrutinize design outputs and the reports of IV&V and certification/regulatory reviews to determine if the complete process as implemented can be treated as equivalent to the recommendations of SG-D-25. In case of Commercial-PDS, the system is already designed and developed for commercial use without knowledge of the unique requirements of particular nuclear applications but it is being used in many commercial applications. Whenever these systems are considered for deployment in I&C systems in NPP then these are to be qualified for the nuclear application as per the standard regulatory review process. Also, system validation tests are carried out for confirmation of system build, functional requirements, performance requirements, interface requirements and safety requirements.

6. Neutron Flux Monitoring System

Neutron Flux Monitoring System (NFMS) measures the neutron flux representing the core flux and processes the signal to get logarithmic power, linear power, period and reactivity covering the measurement range of 10 decades. The functions of the system are:

- To monitor the core status in all states of the reactor – shutdown, fuel handling, start-up, intermediate & power ranges and during design basis events.
- To prevent inadvertent criticality during fuel handling.

6.1.Type and Location of Neutron Detectors

The total neutron flux at core centre varies from $1x10^7$ n/cm^2/s (nv) at shutdown to $8x10^{15}$ nv at nominal power. The neutron flux around th e reactor is very low as neutron shields are provided to protect the components housed inside the main vessel and to reduce the secondary sodium activity. Various options are studied to finalize the detector location. For initial core loading and first criticality, neutron detectors are provided in a special central fuel subassembly which is loaded in the core at the central location. For monitoring during source range (start-up) and intermediate power operation, detectors are provided in control plug and for monitoring during power operation, detectors are provided below the safety vessel. Fig.1 gives the location of neutron detectors.

6.2.Flux Monitoring during Initial Fuel Loading & First Approach to Criticality

In PFBR, the first approach to criticality is planned to be done with steps of fuel loading. After criticality also, full core will be reached in steps of fuel loading. To monitor the core during this stage, three High Temperature Fission Chambers (HTFC) with a sensitivity of 0.1 cps/nv are placed one over the other at the centre of a special central subassembly called Instrumented Central Sub-Assembly (ICSA). These detectors in ICSA are expected to give a count rate of ~ 25 cps with first batch of 52 Fuel Sub-Assembly loading. These detectors are used for neutron flux monitoring during initial core loading and first approach to criticality and also for start-up till Auxiliary Neutron Source is effective. During fuel loading, control plug is rotated, for which the detectors in ICSA are lifted up in the central canal in the control plug and the signal level in ICSA comes down.

In order to effectively monitor the core during the initial fuel loading operation, i.e., when ICSA detectors are lifted up, Boron-10 coated proportional counters (BCC) are provided in control plug locations. These detectors, each with a sensitivity of 12 cps/nv, are divided into two groups, each group consisting of 3 detectors connected in parallel. After full core loading, control plug BCC will be replaced by HTFC detectors.

6.3.Neutron flux monitoring during normal operation

After loading the full core, the reactor operation continues with 0.2 cps/nv HTFC at control plug locations. After studying various options for detectors and instrumentation systems, it is proposed to provide three 0.2 cps/nv HTFC at 3 locations, 120^o apart in the control plug, to monitor the measurement range from shutdown to full power with wide range channels having pulse and Campbell mode from 1 nv to 2x 10^9 nv.

Below the safety vessel, the flux is 1.34×10^5 nv at full power and gamma field is 10 Sv/h (1000 R/h) and temperature is ~ 100°C. With fission chambers of sensitivity 0.75 cps/nv, the signal levels are sufficiently high with required accuracy and response time for full power operation. Hence 5 fission chambers working in pulse mode (3 for safety and 2 for control) are placed below the safety vessel with concrete over the detectors removed for better flux availability.

Signals from control plug detectors are automatically inhibited when flux monitoring is taken over by detectors below Safety Vessel. At any time, only one system is used for safety and control functions.

6.4.Design changes/improvements in FBR compared to PFBR

Based on the experience of design of I&C systems for PFBR, design changes/improvements are made in few cases. These changes are attempted as deign simplification, cost reduction or import substitution.

In FBR 1&2, it is proposed to have detectors only at control plug location, by using detector with higher sensitivity at control plug. The parallel plate design of under vessel detector (with higher sensitivity) will be qualified for high temperature application for use in control plug. Alternatively, the cylindrical design of 0.2 cps/nv HTFC will be modified with HEU to get higher sensitivity of 0.75 cps/nv or better. This will lead to simple design with reduced no. of detectors and electronics.

7. Core Temperature Monitoring System

For monitoring the adequacy of core cooling, temperature at the outlets of all FSA and inlet of the core are measured. These temperature signals are used for detection of core anomalies like plugging of fuel subassemblies, error in core loading, fuel enrichment error and fuel orifice error. It facilitates design validations of reactor physics and thermal hydraulics and burn up management. It provides signals for protection of the reactor from various incidents like SA flow blockage, primary pump speed reduction, transient over power at low power and power failure. These safety actions prevent the coolant, clad and fuel temperatures from reaching the design safety limits.

Chromel-Alumel thermocouples are selected for core temperature monitoring as they have very good radiation resistance, almost linear temperature-emf characteristic over the required range of measurement and proven operating experience in all the fast reactors. Mineral insulated, SS sheathed, ungrounded junction thermocouples of overall diameter 1 mm are used. Probe with two thermocouples are provided in thermowells at the outlets of each Fuel Sub Assembly (FSA). Central subassembly follows different arrangement.

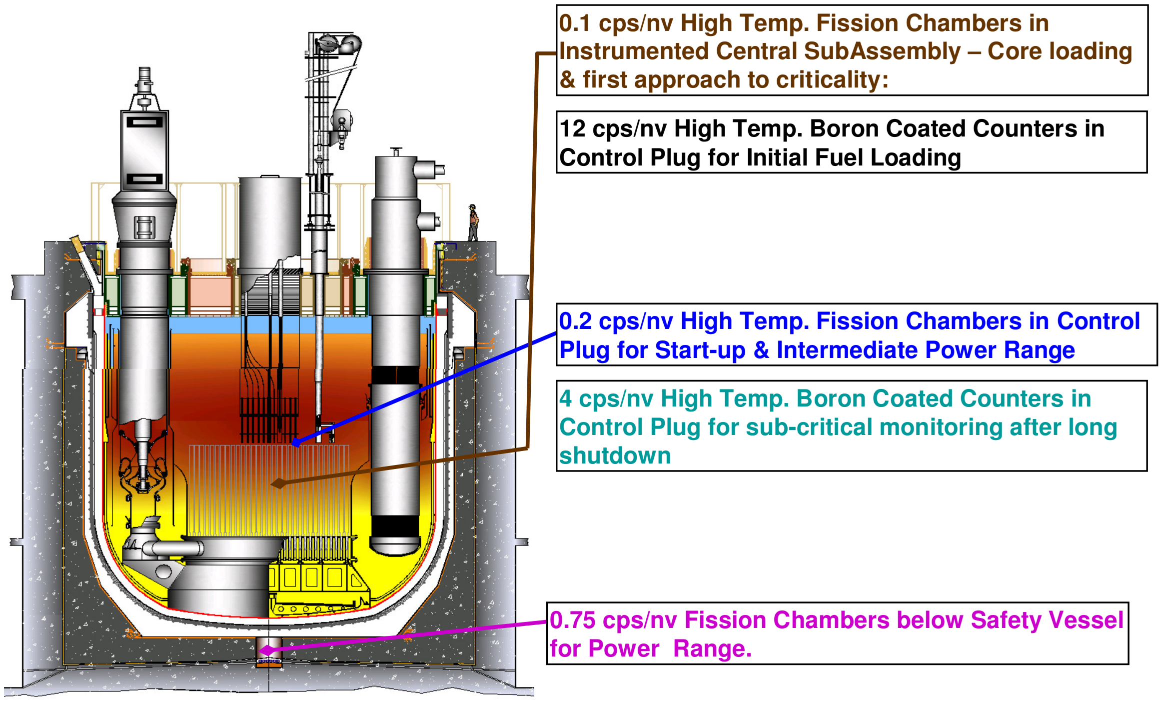

FIG.1 Neutron Detectors for PFBR

In the design adopted for PFBR, the signals are routed to the Local Control Center (LCC) inside Reactor Containment Building (RCB). Thermocouple probes are installed in the thermowells in control plug. Signal leads emerging from control plug is connected through cables to the signal conditioning modules (SCM) in LCC of RCB. Two more disconnectable connectors are provided between the sensor and SCM at the interface of SRP/LRP and LRP/Roof slab. The amplified signal from SCM is routed through leak tight penetrations to outside of RCB. Triplication of signals are done in Control Building (CB) LCC and processed by three Real Time Computers (RTC) located in three LCCs of CB. Total numbers of signals handled by each RTC are large (420). Fig.2 shows a thermocouple probe and the location of thermowells in the control plug. Fig.3 shows the present scheme for core temperature monitoring in PFBR.

7.1.Proposed arrangement for FBR

Probe with 3 thermocouples are developed instead of the probe with 2 thermocouples used in FBTR and PFBR. This improvement in design of probe will help to bring this system in line with the regulatory requirement of independent triple redundant system for safety critical systems. The design of the probe is such that the overall dimension is same as the probe with 2 thermocouples. This modification will not require any change in the design on control plug or any other reactor components. The response time of the modified probe is estimated through experiments and is meeting the requirements.

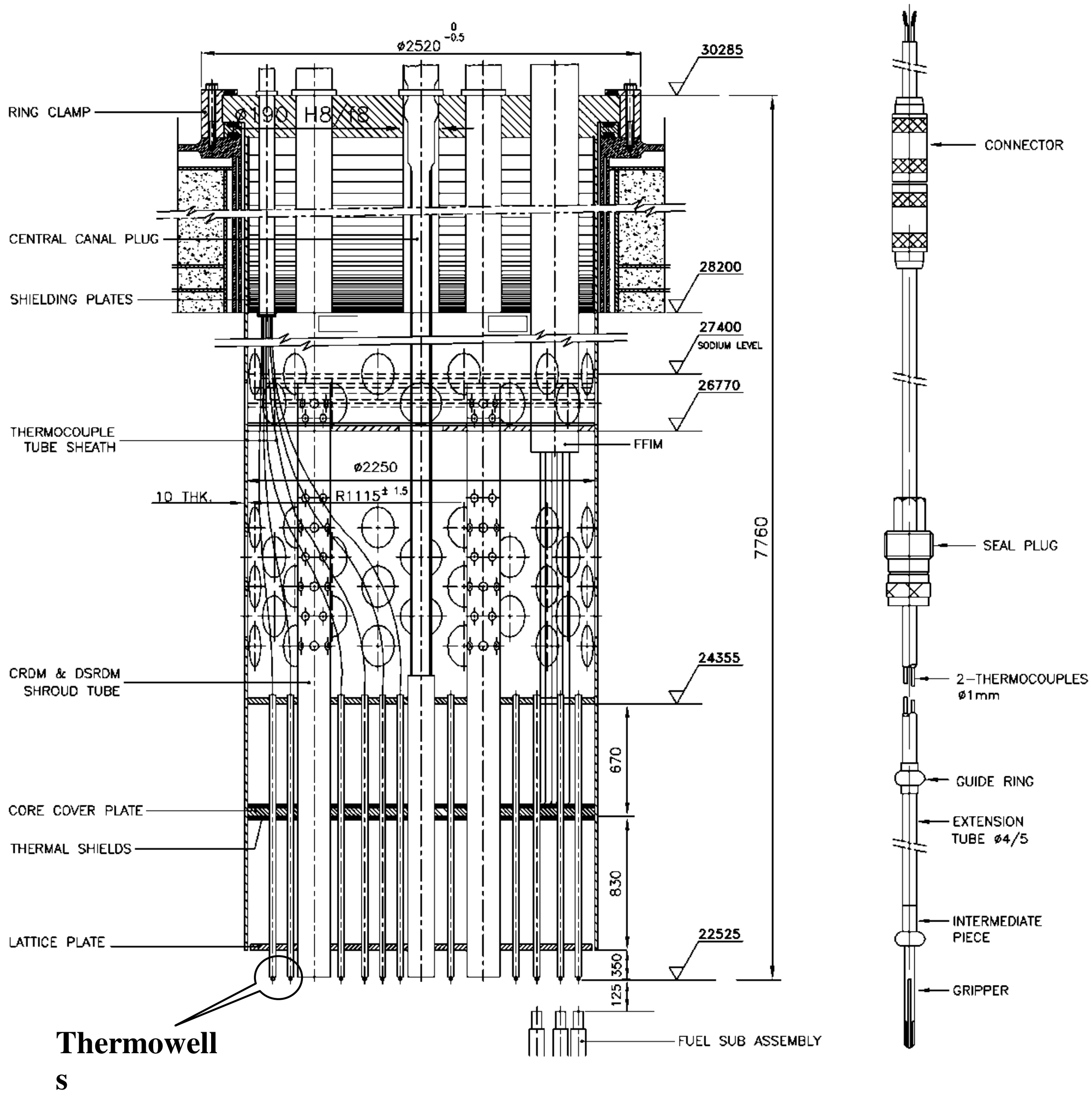

FIG. 2 : Core thermocouples

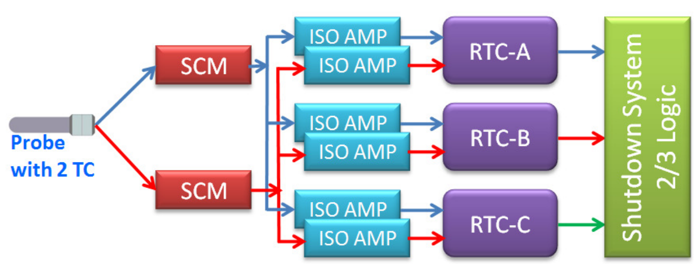

FIG. 3 : Core temperature Monitoring scheme in PFBR

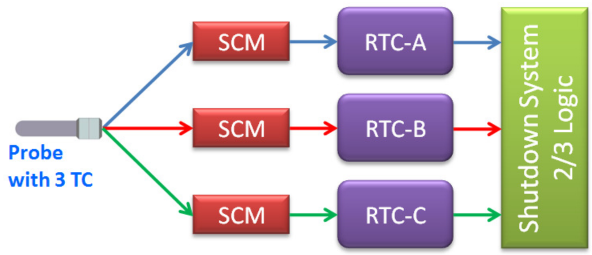

FIG. 4 : Core temperature Monitoring scheme proposed for future FBR

Signals from the three thermocouples of each probe will be connected to independent SCM (Fig.4) and the output of SCM is connected to RTC. In this case each RTC processes 210 signals (compared to 420 in PFBR). Signals are routed independently from sensor to the RTC. In the modified design for future reactors, the SCM and RTC will be located inside RCB in air-conditioned LCC. This will reduce the usage of large volume of cables and leak tight penetrations.

With this arrangement, there is a marginal benefit in unsafe failure probability on demand. For the architecture used in PFBR failure probability on demand is 0.65×10^{-4} and the failure probability on demand for the proposed arrangement is 0.43×10^{-4}. There is an appreciable reduction in spurious trips. In case of PFBR architecture, mean time to spurious trip is 80 days where as with the proposed architecture, it is 128 days.

8. Core flow monitoring

Sodium flow in to the core is measured indirectly by measuring the sodium flow at primary pump discharge. Eddy current flow meters (4 each) are provided in both the pumps. Flow through the core is computed from the sodium flow of each pump. These signals are connected to the reactor protection logic to protect the reactor against primary pipe rupture events. Power to flow ratio is computed from this and used as a signal to protect the reactor. In addition, drop in pump discharge head is computed from the eddy current flow meter signal for protecting the reactor against primary pipe rupture events.

9. Primary pump speed monitoring

Speed of the primary sodium pumps are monitored and used as signal to protect against pump seizure. Three sensors are provided on each pump shaft.

10. Shutdown System Instrumentation

At least two diverse parameters are available for initiating safety actions in case of a design basis event. The selection of instruments is done to ensure that it meets the response time requirements to match with the incident against which it is protecting. The parameters are connected to two independent shutdown systems (SDS-1 & SDS-2). The safety logic systems are cross connected to ensure that actuation of one system will trigger the other shutdown system also, without affecting the individual functionality. Additionally, the ultimate shutdown system provided will ensure that reactor is brought to subcritical state even when the SDS-1 and SDS-2 are ineffective for any reason.

11. Fuel handling system Instrumentation

Design provisions are made in control logic of fuel handling machines to minimize fuel handling errors in the core leading to unintended insertion of positive reactivity. Accurate Positioning of Rotatable Plugs, Transfer Arm and other fuel handling mechanisms will be carried out using Servo Drives with closed loop control. Diverse instruments / sensors will be used for position sensing. Movement of the fuel subassembly will be monitored at every stage. The spent fuel storage pool will be monitored for any coolant leakage using diverse techniques.

12. Design changes/improvements in FBR compared to PFBR

Based on the experience of design of I&C systems for PFBR, design changes/improvements are made in few cases. These changes are attempted as deign simplification, cost reduction or import substitution without compromising the design intent or safety of the plant.

12.1. Other Design Improvements

- ***Sodium Level probes***: Sodium level probes based on mutual inductance principle is used in PFBR. These are very long depending on the height of sodium tank. These probes are difficult to handle because of its slender nature and length. In some areas, building height is increased for facilitating handling of these probes. In FBR 1&2, level probes based on Radar principle will be used. This probe consists of a small antenna projecting into the tank. This is very easy to install and take out. Suitability of this instrument for sodium application is established in sodium loops. Long term behavior in sodium is studied.

- ***Reactor Assembly instruments***: In PFBR, large no. of signals from reactor assembly components is routed through cables with disconnectable connectors in between, to facilitate rotation of plugs. Roof slab area is crowded with large volume of cables.

- ***Wireless technology*** will be introduced in FBR1&2. Transmitters to which sensors are connected will be located on the top of roof slab and the receivers are located on the periphery. This will simplify the design and elimination of connectors will save time during fuel handling campaign. Suitability of wireless technology for this application is established by configuring the system with products available in market.

- ***Trailing cable system***: Trailing cable system of PFBR used for transmitting important signals during rotation of plugs (during fuel handling) is very complex. By adopting wireless technology, this will be simplified in FBR1&2. Also, the difficulties faced in routing of signal cables from mobile fuel handling systems will be eliminated by using wireless technology.

- **Indigenisation efforts**: Some of the components that are imported for PFBR are developed through Indian industries. (Cable penetration assemblies, core temperature probes, electrical heaters). Mineral insulated cables and mineral insulated thermocouples from Indian manufacturers are qualified for application in FBR1&2. PEEK insulated cables will be considered as a cheaper substitute for Mineral Insulated cables in radioactive and high temperature applications.

13. Summary

Design improvements are attempted to simplify the design, improve the economy and improve the reliability. Designs meet AERB safety criteria and attempts are made to meet Gen IV criteria also. Our efforts to manufacture I&C components indigenously has resulted in improved economy and ease of qualification as per codes and guidelines.

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